A Simulation Study on the Size and Angular Location Estimation of Fish Schools Using Spatial Correlation

APL-UW 8012
August 1980

1

A Simulation Study on the Size and Angular Location Estimation of Fish Schools Using Spatial Correlation

by Roger G. Hendershot

APPLIED PHYSICS LABORATORY
UNIVERSITY OF WASHINGTON

APL-UW 8012
August 1980

FOREWORD

This document is the Master's Thesis of Roger C. Hendershot. It is being issued as a technical report for the Advanced Lightweight Torpedo project under Contract N00024-78-C-6018. The work reported is part of a study of digital simulations of high-frequency acoustic backscattering characteristics of fish schools and bottom features. The aim of this study is to provide accurate simulation of false target echoes in the Applied Physics Laboratory's Reverberation Generator (REVGEN) simulator and the Naval Ocean System Center's Hybrid Simulator.

This study is in an early stage, and the work reported here relates to a relatively simple fish school model designed to aid in the interpretation of field data and to provide insight into some of the problems of digital simulation of fish school echoes. As the project continues, detailed point-scatterer models for biological and bottom-feature false targets are to be developed, realized in software, and tested by comparison with field data.

Progress made on a detailed fish school model will be documented in another APL-UW report, "Construction of a Simulated Fish School as a Sonar False Target," by G.E. Lord. That document contains a description of the model and a listing of the REVGEN software that incorporates the model. In that model, each scatterer follows a separate track through the ocean, each track having both deterministic and random components. The Doppler shift and aspect-dependent cross section are computed from tracking information.

In contrast to the REVGEN simulation, the model described in this thesis is simpler in that there is no tracking or "memory" of fish positions on successive pings. This simpler model serves two purposes: (1) it is a convenient means for determining the sensitivity of the simulation output to parameters such as number of point scatterers, distribution of individual scattering cross sections, distribution of Doppler shifts, etc., and (2) it provides a method of determining biases in fish school size estimates made using acoustic data. An understanding of these biases is important in extracting depth and size distributions for the fish schools in the experimental data base.

This thesis emphasizes split-beam processing methods, more particularly, crosscorrelations between split beams. This choice was made because a rather large quantity of field data has already been processed using this technique, with promising results. Also, we have found that the crosscorrelator output is extremely sensitive to changes in simulation parameters and provides a clear indication of the onset of trouble when scatterer density, sampling rate, etc., take on unacceptable values.

ABSTRACT

A computer simulation based on a point scatterer model has been used to investigate the problem of estimating the location and dimensions of fish schools using split-beam processing of hydroacoustic data. Estimates are derived from the temporal crosscorrelation of signals received by transducer halves, the peak correlation amplitude being related to the variance of the scatterer locations (the fish school's width) and the time shift of the peak being related to the mean of the scatterer locations (the fish school's angular position). These estimates are formed with vertically and horizontally separated transducer halves and combined with echo arrival time to provide three-dimensional position and size.

It is demonstrated that fluctuations in the estimated angular size decrease as the ratio of pulse length to echo length decreases.

The effect of additive noise, uncorrelated between acoustic channels, has also been studied. Noise causes width estimates to be biased toward larger values, owing to decorrelation between the acoustic channels. The location estimates, however, remain unbiased for signal-to-noise ratios down to approximately -5 dB.

TABLE OF CONTENTS

	Page
List of Figures	vi
List of Tables	vii
Acknowledgments	viii
Chapter 1: Introduction	1
Chapter 2: Description of the Split Beam Simulation	3
Chapter 3: Documentation of the Simulation Programs	14
3.1 Description of EFILL	15
3.2 Description of SNGLPNG	16
Chapter 4: Analysis and Results of the Simulations	33
4.1 Effects of Uncorrelated Noise	34
4.2 Sources of Fluctuations in the Spatial Estimates	41
Chapter 5: Conclusions	51
List of References	53
Appendix A: Derivation of Spatial Estimates for Nonoverlapping Echoes	55
Appendix B: Relationships between the School Dimensions and the Standard Deviations of the Fish Locations	59
Appendix C: Derivation of the Down-Range Dimension Estimate	61
Appendix D: Listings of Computer Programs	64
Appendix E: Formulation of Amplitude Corrections for Transducer Beam Patterns	80

LIST OF FIGURES

		Page
1	Physical representation of the simulation	5
2	Echo crosscorrelation using two scatterers.	5
3	Signal processing and estimation procedure used in the simulation.	7
4	Split-beam simulation structure	15
5	Block diagram of SNGLPNG.	17
6	Illustration of propagation path lengths.	19
7	Illustration of the effect of uncorrelated noise on the horizontal bearing estimate	38
8	Illustration of the stability of the horizontal bearing estimate versus uncorrelated noise.	38
9	Illustration of biases in horizontal dimension estimates caused by uncorrelated noise.	39
10	Illustration of the fluctuations in the horizontal dimension estimates caused by uncorrelated noise. . . .	39
11	Effect of noise on the down-range dimension estimate. . .	40
12	Conversion from mechanical to electrical degrees.	57
13	Diagram of actual split-beam transducer	80
14	Calibration curves of an actual split-beam transducer . .	82
15	Listing of the computer code used in calculating the second set of beam losses for schools	83
16	Combined transmit and receive beam patterns for the second set of amplitude corrections	84

LIST OF TABLES

Page

1 Illustration of dimension estimate fluctuations versus fish school dens. y and transmit pulse shape. 44

2 Illustration of the reduction in relative dimension estimate fluctuations for larger school sizes (x' dimension) versus transmit pulse length. 45

3 Illustration of the effect of ascribing random amplitudes and Doppler shifts to the point scatterers 48

4 Illustration of high standard deviations of dimension estimates for a rectangular transmit pulse and low sampling frequency 50

5 Listing of EFILL 65

6 Listing of SNGLPNG 66

ACKNOWLEDGMENTS

The author expresses his sincere appreciation for the guidance, encouragement, and constant support provided by Professor Darrell R. Jackson, without whom this work would not have been possible. Thanks are also due the staff members of the Applied Physics Laboratory at the University of Washington for their advice and help.

This research was conducted under the direction of the Advanced Lightweight Torpedo project, PMS 406T2 (James D. Grembi), and the Naval Ocean Systems Center, San Diego, under NAVSEA Contract N00024-78-C-6018.

CHAPTER 1

INTRODUCTION

In hydroacoustic assessment of fish populations, the ability to retrieve spatial characteristics from fish school echoes is highly desirable, but generally difficult. Estimations of the overall school size and location are of interest in determining, for example, behavior patterns and mean target strengths of fish in their natural environment. Narrowbeam sector-scanning arrays can be used to determine spatial properties. The use of split-beam systems is another attractive possibility because of their relative low cost and simplicity compared with sector-scanning systems. Split-beam systems have been used to determine school depth[1] and target strengths of single fish.[2]

In this thesis, computer simulations are used to investigate split-beam techniques for estimating overall school size and location. Chapter 2 provides a general description of the split-beam method. Fish schools are simulated using ellipsoids filled with point scatterers, and echoes from these schools are constructed using the single scattering approximation. The crosscorrelation of these echoes received by the quadrants of the split-beam transducer is then used to calculate the size and location estimates.

A description of the simulation programs is given in Chapter 3. A series of programs is used to study the effect of the school characteristics, noise, and sampling parameters on the spatial estimates. In Chapter 4 the results of the simulations are given along with supporting analysis for simplified situations. Biases in the dimension estimates resulting from the decorrelating effect of the noise, and other sources of fluctuations in the estimates are illustrated. Conclusions about the errors in split-beam spatial estimates follow in Chapter 5.

CHAPTER 2

DESCRIPTION OF THE SPLIT-BEAM SIMULATION

An introduction to the split-beam method and a general description of the computer simulation are presented in this chapter. The formulation of crosscorrelations of the echo signals using quadrature sampling is given along with the relationship between these crosscorrelations and the angular location and dimension estimates.

A physical representation of the split-beam technique used in the computer simulation is shown in Fig. 1. This system uses a multiple-element transducer with the elements combined to form the four transducer-half signals labeled left, right, up, and down. In general, the target will not lie on the axis of the transducer beam and the four signals will be displaced in time from one another. This time difference, measured by using the time shift at the peak correlation between the signals, can be used to estimate the bearing to the center of the target. The crosscorrelation of the left-right signal gives the horizontal bearing and that of the up-down signal gives the vertical bearing.

The magnitudes of the crosscorrelations can be used to estimate the target's angular size. The greater the angle covered by the target, the lower the crosscorrelation. This concept can be illustrated with a simple example. A single scatterer will result in identical, time displaced signals whose normalized peak crosscorrelation will equal unity. When a second scatterer is added, the arrival time of its echo relative to the other scatterer's will differ for each signal as can be seen by examining the path lengths in Fig. 2. The signal envelopes at transducers A and B are $s_A(t)$ and $s_B(t)$, where $s_B(t)$ illustrates the possibility of destructive interference between the two scatterer returns. Since these signals differ, their normalized peak crosscorrelation will be less than unity. Additional scatterers will result in a further decrease in the peak crosscorrelation.

The fish school is represented in the simulation by an ellipsoid filled with point scatterers whose locations are randomly chosen. In the simulations reported here, the ellipse rotation angle, θ, equals zero, so the x' axis will always point to the center of the transducer. The angle ψ measured in the left-right plane of the transducer is the target bearing relative to the beam axis.

The number of point scatterers per cubic meter in the ellipsoid is typically around 0.3. Multiple scattering effects should be minimal for actual fish schools with these densities.[3] The onset of first-order multiple scattering occurs when the term $\rho\langle\sigma_t\rangle L \approx 0.1$. This term is known as the optical distance within the scattering medium, where ρ is the density of the scatterers, $\langle\sigma_t\rangle$ is the average extinction cross section of the individual scatterers, and L is the round trip acoustical path length in the scattering medium. A typical optical distance simulated in this study is for an ellipsoid with x', y', and z dimensions of 10 m,

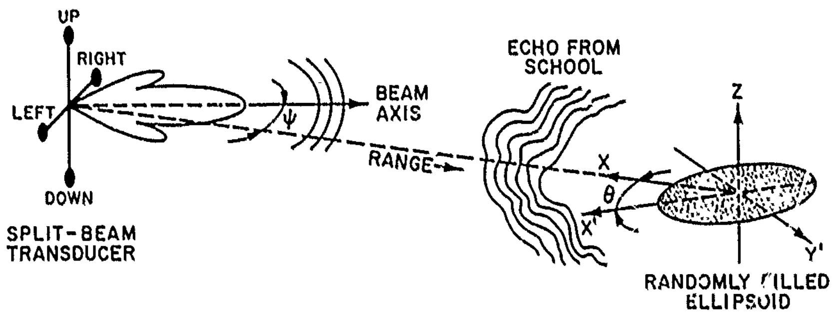


Figure 1. Physical representation of the simulation.

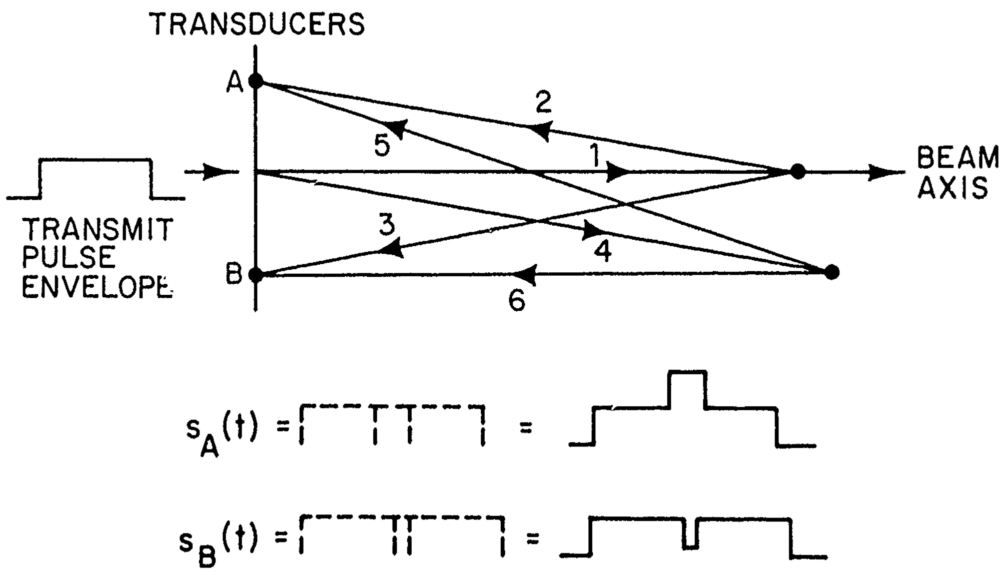


Figure 2. Echo crosscorrelation using two scatterers.

15 m, and 5 m, and containing 100 fish. For this situation $\rho = 100/(4/3 \cdot \pi \cdot 2.5 \cdot 7.5 \cdot 5) = 0.255$ fish/m^3, and $L = 20$ m. The extinction cross section of a fish of length 30 cm is approximately 30 cm^2 with fluctuations from 3 to 300 cm^2 depending on the fish's orientation. The resulting optical distance is 0.015, which is well below the onset of first-order multiple scattering.

The point scatterers are assigned scattering amplitudes and Doppler shifts. The scattering amplitudes either are equal or are randomly chosen from a Rayleigh distribution[4] using a different distribution mean for each scatterer. The resulting amplitudes fluctuate approximately 6 dB. The scattering amplitude of each scatterer is also corrected for the strength of the transmit and receive beam patterns. The Doppler shifts are either zero or chosen from a uniform distribution ranging from 20 to 100 Hz using a 30 kHz carrier frequency reflecting relative motions ranging from 1 to 5 kn.[5]

Four echo delays for each scatterer are computed using path lengths measured from the center of the transducer to the scatterer and back to the left, right, up, and down centers. No multiple scattering paths are included. The effects of differential spherical spreading and absorption losses associated with the path lengths are negligible for the geometries simulated and are not included.

Next, samples of the fish school echo are constructed as shown in Fig. 3. Because the echo signal is assumed to be narrowband,

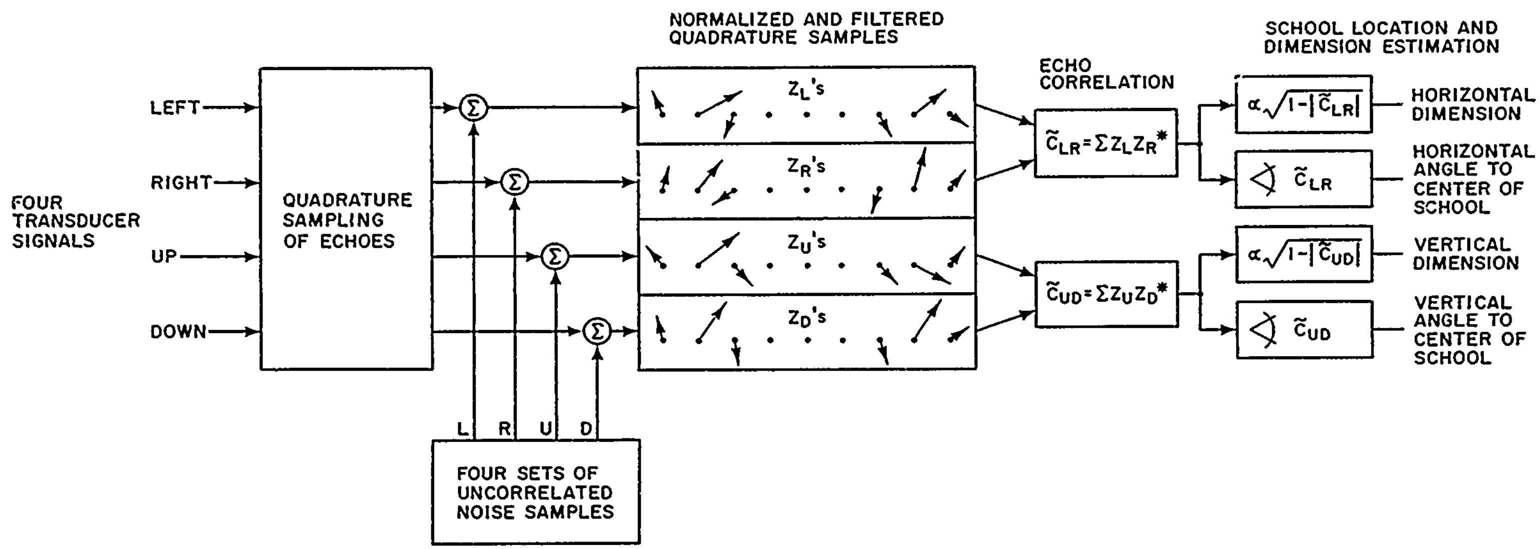


Figure 3. Signal processing and estimation procedure used in the simulation.

and to retain phase information, samples of the signals are taken in quadrature form. If the echo from a scatterer is present at the time a sample is taken, the scatterer's contributions to the quadrature components of that sample are included in the following summations.

The i^{th} quadrature samples taken at time t_i are given by

$$z_L(i) = \sum_k A(k) B_{LR}(k) P[t_i - \tau_L(k)] \exp\left\{ j2\pi [f_o + f_d(k)] \cdot \tau_L(k) \right\}$$

$$z_R(i) = \sum_\ell A(\ell) B_{LR}(\ell) P[t_i - \tau_R(\ell)] \exp\left\{ j2\pi [f_o + f_d(\ell)] \cdot \tau_R(\ell) \right\} \qquad (1)$$

$$z_U(i) = \sum_m A(m) B_{UD}(m) P[t_i - \tau_U(m)] \exp\left\{ j2\pi [f_o + f_d(m)] \cdot \tau_U(m) \right\}$$

$$z_D(i) = \sum_n A(n) B_{UD}(n) P[t_i - \tau_D(n)] \exp\left\{ j2\pi [f_o + f_d(n)] \cdot \tau_D(n) \right\},$$

where the summation is over the scatterer echoes k, ℓ, m, and n, present at the left, right, up, and down transducer centers at time t_i; A( ) is the scattering amplitude; B( ) is the combined transmit and receive beam correction for the left-right or up-down transducer halves; P( ) is the amplitude of the scatterer echo envelope at time t_i; f_o is the carrier frequency (30 kHz); f_d is the Doppler shift; $\tau(\ )$ is the round-trip delay time to the left, right, up, or down transducer center.

The envelopes of the scatterer echoes, denoted by P, are assumed to be identical to the envelope of the transmit pulse, and no changes caused by the scatterer or the medium are included. Also note that because of the difference in arrival times at the four quadrants, a scatterer that is included in the summation for the left quadrature sample, for example, may not be included in the summation for the right quadrature sample; hence, the different subscripts k, ℓ, m, and n.

Uncorrelated noise is included by adding two random white Gaussian noise components to the echo samples. The signal-to-noise ratio (SNR) is defined for each echo as the ratio of the energy of the signal samples to the energy of the noise samples. These signal-plus-noise samples are then digitally filtered by a single-pole filter whose 3 dB bandwidth is nominally 1 kHz.

The four sets of filtered samples are each normalized by the square root of their respective total echo energies. The quadrature samples in this form are shown as Z_L, Z_R, Z_U, and Z_D in Fig. 3.

The next step in the signal processing procedure is the echo crosscorrelation. In general the crosscorrelation of two sets of echoes would be a function of the shift in samples between the two sets. However, the information required to estimate the target's angular position and dimensions is contained in an expression where no shift is used. This expression is

$$\tilde{C}_{LR}(0) = \sum_i Z_L(i)\, Z_R^*(i)$$
$$\tilde{C}_{UD}(0) = \sum_i Z_U(i)\, Z_D^*(i)\,, \tag{2}$$

where the summation is over all echo samples. The need for computing only one crosscorrelation term, which is an advantage of the split-beam system, can be understood by considering the crosscorrelation of two signals c(t) computed in continuous time. This crosscorrelation is related to the continuous time quadrature form by the equation

$$c(t) = \mathrm{Re}\left\{\tilde{c}(t)\ e^{j2\pi f_o t}\right\}\,, \tag{3}$$

where $\tilde{c}(t)$ is the continuous time form of Eq. 2 and f_o is the carrier frequency.

Since the echo signals are assumed to be narrowband, $\tilde{c}(t)$ is a slowly varying function with respect to f_o. If the target's location is restricted to the main lobe of the transducer beam patterns, the maximum correlation at time t_{max} will occur within $T_o/2$ of c(0), and $\tilde{c}(t_{max}) \approx \tilde{c}(0)$.

The maximum crosscorrelation $c(t_{max})$ is related to the target dimension whereas t_{max} is related to the location. This will occur when $-2\pi f_o t$ equals the angle of $\tilde{c}(t)$ in Eq. 3. Given that $\tilde{c}(t)$ is slowly varying, $|\tilde{c}(0)| \approx c(t_{max})$ and $\arg\{\tilde{c}(0)\} = -2\pi f_o t_{max}$. Accordingly, the sampled version of $\tilde{c}(0)$ provides sufficient information to calculate the dimension and location estimates.

Expressions for the horizontal and vertical dimension and angular location estimates are easily obtained for the case where individual fish echoes are not overlapping (see Appendix A). The analysis for the more general case where many fish contribute to a given quadrature sample is given by Gardner and Jackson.[6] Both analyses result in the following expressions for the horizontal and vertical spatial estimates.

$$
\begin{aligned}
D_H &= \frac{\sqrt{2}}{\gamma_H} \sqrt{1-|\tilde{C}_{LR}(0)|}\ (2\sqrt{5})\ R \qquad (m) \\
D_V &= \frac{\sqrt{2}}{\gamma_V} \sqrt{1-|\tilde{C}_{UD}(0)|}\ (2\sqrt{5})\ R \qquad (m) \\
\theta_H &= -\frac{1}{\gamma_H} \tan^{-1} \frac{\mathrm{Im}\{\tilde{C}_{LR}(0)\}}{\mathrm{Re}\{\tilde{C}_{LR}(0)\}} \qquad (deg) \\
\theta_V &= -\frac{1}{\gamma_V} \tan^{-1} \frac{\mathrm{Im}\{\tilde{C}_{UD}(0)\}}{\mathrm{Re}\{\tilde{C}_{UD}(0)\}}\ , \qquad (deg)
\end{aligned}
\tag{4}
$$

where R is the target range and γ_H and γ_V are the conversion factors from mechanical to electrical degrees. $\gamma_H = (2\pi f_o S_H)/c$ and $\gamma_V = (2\pi f_o S_V)/c$, where S_H is the separation between the horizontal transducer centers (5.7 cm), S_V is the separation between the vertical transducer centers (8.6 cm), and c is the assumed sound velocity in water (1500 m/s).

The term $\sqrt{2}/\gamma\ \sqrt{1-|\tilde{C}(0)|}$ represents the standard deviation (with respect to the random positions of the scatterers) of the azmuthal angle. The term $2\sqrt{5}$ converts the standard deviation of a collection of points bounded by an ellipsoid to the dimension of the ellipsoid (see Appendix B).

The down-range (x' direction) dimension estimate, D_{DR}, is calculated using the energies in th uadrature samples (see Appendix C). The down-range dimension is given by

$$D_{DR} \approx \frac{1800}{f_s} \frac{\left(\sum_i |Z(i)|^2\right)^2}{\sum_i |Z(i)|^4} , \tag{5}$$

where f_s is the sampling frequency and the summations are over all quadrature samples of a transducer signal.

REFERENCES

1. D.R. Jackson and G.L. Thomas, "Acoustic Measurement of Fish Schools Using Array Phase Information" (abstract), OCEANS '79, IEEE Publ. No. 78CH1478-7 OEC, September 1979, p. 59.

2. T.J. Carlson and D.R. Jackson, "Empirical Evaluation of the Feasibility of Split Beam Methods for Direct In Situ Target Strength Measurement of Single Fish," APL-UW 8006, Applied Physics Laboratory, University of Washington, January 1980.

3. D.W. Lytle and D.R. Maxwell, "Hydroacoustic Estim tion in High Density Fish Schools," Proc. Conf. Acoustics in Fisheries, Hull College of Higher Education, Hull, England, 26 and 27 September 1978.

4. G.C. Goddard and U.G. Welsby, "Statistical Measurement of the Acoustic Target Strength of Live Fish," Departmental Memorandum No. 456, Department of Electronic and Electrical Engineering, University of Birmingham, January 1975.

5. R.J. Vent, I.E. Davies, R.W. Townsen, and J.C. Brown, "Fish School Target Strength and Doppler Measurements," Report No. NUC-TP-521, Naval Undersea Center, San Diego, California, July 1976.

6. W.A. Gardner and D.R. Jackson, "Extraction of Spatial and Temporal Parameters of a Body of Scatterers Using Cross-correlation," in preparation.

CHAPTER 3

DOCUMENTATION OF THE SIMULATION PROGRAMS

In this chapter, a more detailed account is given of the system of programs used in simulating the split-beam system. These programs are mostly written in Extended FORTRAN language, and were used at the facilities of the University of Washington Academic Computer Center. A listing of the programs with sample inputs and outputs is included in Appendix D.

The computer simulation of the split-beam method is accomplished using the system of programs and files shown in Fig. 4. The main component is the program called SNGLPNG which simulates a single ping on an elliptical fish school and estimates the school's size and location. SNGLPNG obtains data needed for each run from two sources. The input file contains the desired parameters for the run, including information on the fish school and echo sampling procedure. The results of previous runs which can be used in the current run are contained in a second input file from tape storage. If no previous runs have been made on a particular school, then the initial inputs to SNGLPNG, created by EFILL, are the scatterer locations within the ellipsoid. The results of the simulation for several pings are than analyzed and plotted using other FORTRAN programs with Numerical Plotting System routines.

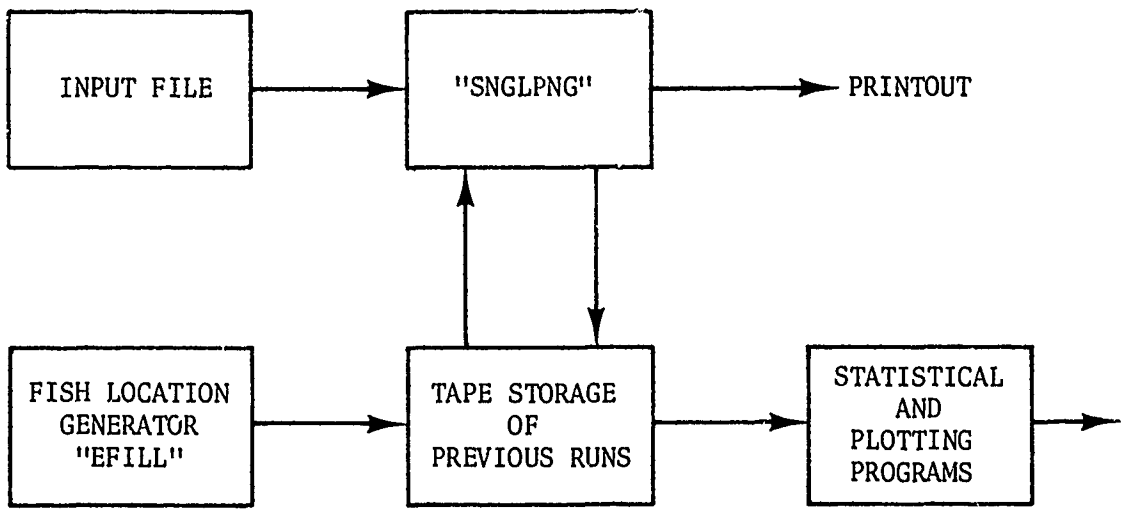


Figure 4. Split-beam simulation structure

3.1 Description of EFILL

The starting point of the simulation is the program EFILL. This program simply generates random locations within a specified ellipsoid and stores these locations on tape. Three random numbers corresponding to the x, y, and z coordinates of each fish are generated using the intrinsic computer function, RANF. This function produces independent, uniformly distributed random numbers within the range 0,1. The three values from RANF are shifted to the range (-1,1) by subtracting 0.5 and doubling each value. The corresponding location is tested to determine whether it lies within a unit sphere. If the point does not lie in the sphere, three new random numbers are generated; otherwise, a fish location is obtained by multiplying the x, y, and z coordinates by the values of a, b, and c used in the following expression for defining the ellipsoid:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1.$$

This process is repeated until the desired number of fish locations is obtained.

The format used to store these locations on tape is compatible with future outputs of SNGLPNG which contain additional information about the fish such as scattering amplitudes and Doppler shifts. Since EFILL doesn't calculate this information, that space is filled with zeroes.

3.2 Description of SNGLPNG

The program SNGLPNG is composed of five sections as shown in Fig. 5. The information gathered in the input section determines the program flow through the remaining sections. For example, if only the sampling frequency is changed from a previous run, the fish school data are taken from the previous run, and the program skips directly to the echo processing section.

Input Section

The input section reads data from the input file and tape storage. The desired parameters for the run are provided by the

INPUT SECTION

- Desired parameters
- Parameters from a previous run

↓

FISH SCHOOL SECTION

- Propagation delays to the four transducer centers
- Random scattering amplitudes and beam losses
- Random Doppler shifts

↓

ECHO PROCESSING SECTION

- Quadrature samples of school echo
- Quadrature samples of noise
- Digital filtering of signal plus noise samples
- Crosscorrelation of samples
- Fish school location and dimension estimates

↓

DATA TAPE STORAGE SECTION

↓

PRINT SECTION

- Individual fish characteristics
- Normalized samples of signal plus noise
- Unnormalized signal and noise samples
- Input data summary and computed results

Figure 5. Block diagram of SNGLPNG

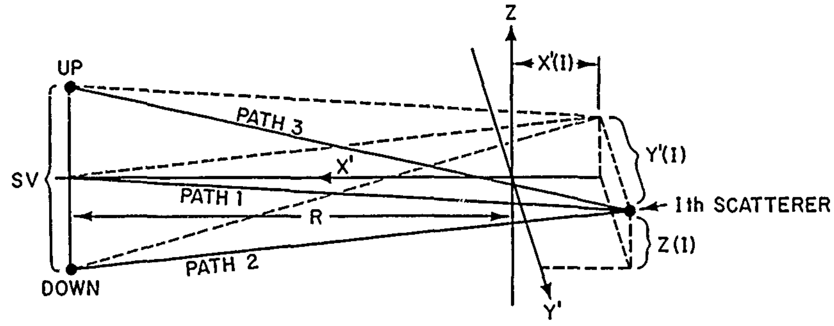
input file and a summary of the parameters used in a previous run is found on tape storage. If the fish school is the same in both files, the program skips to the echo processing section.

Fish School Section

The fish school section performs calculations involving the individual scatterers. Round-trip propagation delays, a random scattering amplitude, corrections to this amplitude to account for beam patterns, and a random Doppler shift are computed for each scatterer. If the desired location determined by the range, R, and bearing, ψ, or the desired orientation determined by the aspect angle, θ, differ from those of the previous run, then new propagation delays are needed. The path lengths associated with these delays are determined by the geometry shown in Fig. 6. The total acoustic path lengths for the left, right, up, and down transducer centers are path 1 plus path 5, path 4, path 3, or path 2, respectively. The propagation delays are these lengths divided by the assumed speed of sound in water (1500 m/sec).

New amplitude corrections reflecting each scatterer's new position in the beam patterns must also be computed if the school location or orientation is changed. Expressions of the form $\left|\frac{\sin\theta}{\theta}\right|^{m\theta+c}$ are fitted to transducer calibration curves from an actual split-beam transducer. The results of these fits are given in Appendix E.

SIDE VIEW

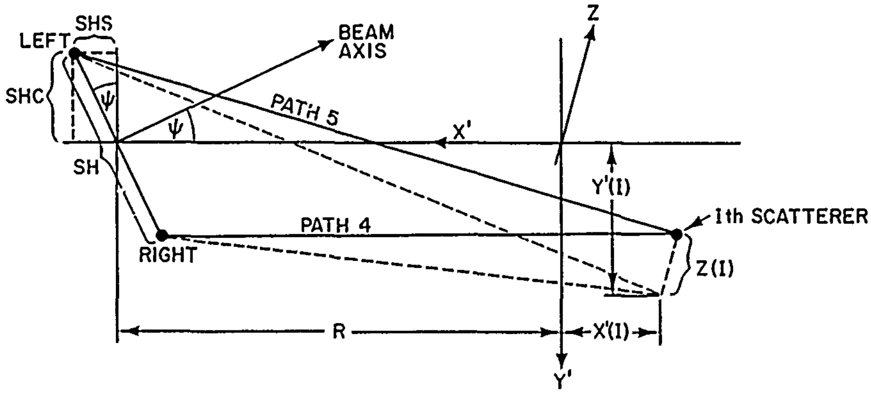


$$\text{PATH 1} = \left\{[R + X(I)]^2 + Y(I)^2 + Z(I)^2\right\}^{1/2}$$

$$\text{PATH 2} = \left\{[R - X(I)]^2 + Y(I)^2 + [Z(I) + SV/2]^2\right\}^{1/2}$$

$$\text{PATH 3} = \left\{[R - X(I)]^2 + Y(I)^2 + [Z(I) - SV/2]^2\right\}^{1/2}$$

TOP VIEW



$$SHS = SH/2 \cdot \sin\psi \qquad SHC = SH/2 \cdot \cos\psi$$

$$\text{PATH 4} = \left\{[R - X(I) + SHS]^2 + [Y(I) - SHC]^2 + Z(I)^2\right\}^{1/2}$$

$$\text{PATH 5} = \left\{[R - X(I) - SHS]^2 + [Y(I) + SHC]^2 + Z(I)^2\right\}^{1/2}$$

NOTE: Positive values of ψ are to the left of the beam axis.

Figure 6. Illustration of propagation path lengths.

The horizontal and vertical angles describing the angular location of each fish are given by

$$\text{THH} = \psi - \tan^{-1}[y/(R-x)] \qquad \text{(rad)}$$

and (6)

$$\text{THV} = \tan^{-1}\left[z/\sqrt{(R-x)^2 + y^2}\right] \qquad \text{(rad)},$$

where x, y, and z are the fish coordinates, and R and ψ are the range and bearing to the center of the school.

This two-dimensional location is converted to an equivalent horizontal or vertical angle which has the same beam strength by the equation

$$\text{THHEQ} = \sqrt{\text{TTH}^2 + (\varepsilon \cdot \text{THV})^2} \;\; \pi/0.439 \qquad \text{(rad)}$$

or (7)

$$\text{THVEQ} = \sqrt{(\text{THH}/\varepsilon)^2 + \text{THV}^2} \;\; \pi/0.291 \qquad \text{(rad)},$$

where ε is the horizontal to vertical eccentricity of each beam pattern. THHEQ is calculated for the transmit and up-down beam patterns, and THVEQ is calculated for the transmit and left-right beam patterns. The factors $\pi/0.439$ and $\pi/0.291$ are needed to make the first null of $\sin\theta/\theta$ correspond to the main lobe boundaries of the calibration curves.

THHEQ or THVEQ can now be used in the equations chosen to fit the horizontal or vertical calibration curves for the transmit, left-right, and up-down transducer sections. These equations determine the beam losses of the transmit signal combined with either the left-right or the up-down echo.

$$BCL = \left[\left| \frac{\sin(THVEQS)}{THVEQS} \right|^{E1} + \left| \frac{\sin(THVEQ)}{THVEQ} \right|^{E2} - 2 \right] \cdot 45.0 \quad (dB)$$

$$BCU = \left[\left| \frac{\sin(THHEQS)}{THHEQS} \right|^{E3} + \left| \frac{\sin(THHEQ)}{THHEQ} \right|^{E4} - 2 \right] \cdot 45.0 \quad (dB) \tag{8}$$

where

$$\left.\begin{matrix} E1 \\ E2 \\ E3 \\ E4 \end{matrix}\right\} = 0.017189 \cdot \left\{\begin{matrix} THVEQS \\ THVEQ \\ THHEQS \\ THHEQ \end{matrix}\right. + 2.$$

THHEQS and THVEQS are computed for the transmit beam, THVEQ for the left-right beam, and THHEQ for the up-down beam.

If there are no changes in the school location or orientation, then the propagation delays and beam corrections from the previous run are read from tape storage. The program then proceeds to the scattering amplitude calculations. If new amplitudes are desired, they are generated from a Rayleigh process. The distribution function for a Rayleigh process is given by .

$$y = P(x) = 1 - e^{-x^2/2\alpha^2} .$$

If values of y are chosen independently from a uniform distribution ranging from zero to one, the inverse of P is

$$x = P^{-1}(y) = \sqrt{-2\alpha^2 \ell n\, y} \quad ,$$

and the corresponding values of x will be Rayleigh distributed. The computer function, RANF, generates such values of y for each fish. The value α, which is proportional to the mean of the Rayleigh distribution, is also generated by RANF for each fish, and is shifted to range uniformly from 0.5 to 1.5. The result is that the amplitude for each fish is chosen from a Rayleigh distribution; however, the distribution mean is chosen independently for each fish, simulating a different size for each fish.

If no changes were needed in the amplitudes, the previous amplitudes are read from tape storage, and the program proceeds to the Doppler shift calculations. The Doppler shifts are generated independently from a uniform distribution ranging from 20 to 100 Hz when a 30 kHz carrier frequency is used. Random numbers generated by RANF are shifted from the range (0,1) to obtain those Doppler shift values. Note that the Doppler shifts, amplitudes, and locations are generated independently and thus are uncorrelated.

Echo Processing Section

The next part of SNGLPNG is the echo processing section. The main functions of this section are shown in Fig. 3. The first task is the formation of the quadrature samples. The propagation delays are scanned and the times of the first and last samples are determined. The first sample is computed one sampling period after the arrival of the first echo, and the last sample is computed at the last sampling interval prior to the end of the echo. Signal and noise samples are calculated at the desired sampling rate until the end of the last fish echo. If the signal is filtered, additional samples are calculated from the decaying filter output.

In order to achieve the desired signal-to-noise ratio, the gain or magnitude of the noise samples is varied. This gain factor is determined by the expected values of the signal and noise energies, so the actual SNR's obtained in the simulation should fluctuate around the desired value. The expected signal and noise energies are initially computed for the case where no filter is applied. For a rectangular transmit pulse, the expected signal energy is the sum of the received energies (corrected amplitude squared) from all fish times the number of samples taken of each fish echo. It is assumed that the incidences of constructive interference between fish echoes will be counterbalanced by incidences of destructive interference.

The expected energy of the left-right echoes will differ from that of the up-down echoes because of the difference in beam patterns. The expected signal energy used to calculate the noise gain factor is the average of the left-right and up-down expected energies.

For a Hanning transmit pulse, the expected energy is reduced from the rectangular case by the ratio of the energy in the two pulses. The energy in a unit amplitude rectangular pulse is equal to the pulse width, PW, times the amplitude squared.

The energy in a Hanning pulse with unit peak amplitude is given by

$$E = \frac{PW}{\pi} \int_{0}^{\pi} \sin^4 t \, dt = \frac{3}{8} PW.$$

Therefore the expected signal energy using a Hanning pulse is 0.375 times the expected energy using a rectangular pulse of the same length.

To calculate the expected energy of the noise samples, the process from which these samples are generated must be known. The real and imaginary components of each noise sample are independent identically distributed normal random variables having zero mean and unit variance (i.i.d. N(0,1)). The method of generating these samples will be discussed later. The expected energy in a noise sample is equal to the expected value of the magnitude squared which is the sum of the component variances since the magnitudes have zero mean values. The total noise energy expected is then two times the number of samples.

Given the expected signal energy and a desired SNR, a gain factor is computed by the subroutine NGAIN. The noise samples, when multiplied by this gain factor, will have an expected energy necessary to obtain the desired SNR.

The next step in the echo processing section is to compute the unfiltered signal samples. This process is also described in Chapter 2. For each sample time, t_i, the magnitude of the echo envelope is computed for each fish by the function PULSE. If the echo from a fish is present at the transducer, the value of the envelope is equal to one for the rectangular pulse or $\sin^2(t_i-\tau)$ for the Hanning pulse, where τ is the propagation delay to the transducer-half center. If the fish has not yet arrived at or has already passed the transducer, the value returned by PULSE is zero. A nonzero value from PULSE causes that fish echo to be included in the sample described by Eq. 1. Additional signal samples are computed at the desired sampling rate for the duration of the school echo.

An equal number of noise samples are now calculated using the RANF function. As stated earlier, the real and imaginary components of the noise samples are i.i.d. N(0,1) random variables. To obtain these components, two uniformly distributed outputs from RANF are used in the equations

$$R = \sqrt{-2 \ln [\text{RANF}(0.)]}$$

$$\theta = 2\pi \ \text{RANF}(1.)$$

$u = R\cos\theta$

$v = R\sin\theta.$

The noise sample is composed of the components u and v multiplied by the gain factor computed in NGAIN.

If the signal and noise samples are to be filtered, then the program proceeds to the filter calculations. A single-pole digital filter is used whose transfer function is given by

$$H(z) = \frac{1-a}{1-az^{-1}} .$$

This corresponds to the iterative equation

$$y_n = (1-a)x_n + a\, y_{n-1} , \tag{9}$$

where x and y are the input and output of the filter, and the subscripts n and n-1 denote the n^{th} and preceding values of the sequences. Given a 3 dB bandwidth frequency, f_{bw}, the value of "a" can be determined. The steady-state transfer function is obtained by replacing z by $e^{j\omega T_s}$;

$$H(e^{j\omega T_s}) = \frac{1-a}{1-ae^{-j\omega T_s}} .$$

At the 3 dB frequency, the magnitude of the steady-state transfer function squared is 0.5 by definition, so the value of "a" for a given f_{bw} is found by solving

$$0.5 = \left|\frac{1-a}{1-ae^{-j2\pi f_{bw}/f_s}}\right|^2 = \frac{(1-a)^2}{1 - 2a\cos(2\pi f_{bw}/f_s) + a^2} \tag{10}$$

or

$$a = -\cos(2\pi f_{bw}/f_s) + 2 - \sqrt{[2\cos(2\pi f_{bw}/f_s)-4]^2 - 4} / 2 .$$

Values of "a" range from 0.172 to 1.0, corresponding to values of f_{bw} from $f_s/2$ to 0.

The first use of the filter is to compute the expected energy of the filtered signal samples. Again the assumption is made that the constructive and destructive interferences between individual fish echoes cancel each other, and the expected energy is the sum of the filtered individual fish echoes. The integration of the filtered rectangular and Hanning pulses is performed numerically by summing the results of Eq. 9. The sampling interval is the pulse width divided by 10 for the rectangular pulse and by 50 for the Hanning pulse. The process is stopped when the energy of a sample is less than 1% of the sum of the energies of the previous samples.

The expected filtered noise energy is found analytically by finding the ratio of the filtered to unfiltered noise energies in the frequency domain. The frequency spectrum of the filtered noise is the product of the filter spectrum times the constant spectrum of the unfiltered white Gaussian noise. By Parseval's theorem, the integral of the square of the spectrum magnitude is equal to 2π times the integral of the signal energy in the time domain. Thus the ratio of the filtered to unfiltered noise energies can be found by integrating each spectrum over a range equal to one period of the filtered spectrum and computing the ratio of the results. The integral of the filtered spectrum is

$$T_s \int_0^{2\pi} \frac{(1-a)^2}{1 + a^2 - 2a \cos\theta} d\theta = \frac{2\pi \cdot T_s \cdot (1-a)}{1+a} ,$$

where the variable change $\omega T_s \to \theta$ is made.

The integral of the unfiltered spectrum involves a constant spectrum of unit height,

$$T_s \int_0^{2\pi} 1 \, d\theta = 2\pi \, T_s ,$$

and the ratio of unfiltered to filtered expected noise energies is $(1-a)/(1+a)$.

Before the signal and noise samples can be filtered, an initial value for the filtered noise just prior to the first signal sample must be computed. The expected value of this noise sample is

$$\begin{aligned} E[y_0] &= E[ay_{-1} + (1-a)x_0] \\ &= E\{a[ay_{-2} + (1-a)x_{-1}] + (1-a)x_0\} \\ &= (1-a)\ E[x_0 + ax_{-1} + a^2x_{-2} + \cdots] \\ &= (1-a)\ E[x]\ (1 + a + a^2 + \cdots) \\ &= E[x], \end{aligned}$$

where

$$E[x] = E[x_0] = E[x_{-1}] = \cdots .$$

The variance of y_o can also be expressed in terms of the input variable x.

$$E[y_o^2] = E\{(1-a)^2 [x_o + ax_{-1} + a^2x_{-2} + \cdots]^2\}$$

$$= (1-a)^2 E[x_o^2 + a^2x_{-1}^2 + a^4x_{-2}^2 + \cdots]$$

$$= (1-a)^2 E[x^2] (1 + a^2 + a^4 + \cdots)$$

$$= \frac{1-a}{1+a} E[x^2] ,$$

where

$$E[x_{n-u} x_{n-v}] = 0 \qquad \text{except for } u = v$$

and

$$E[x^2] = E[x_{n-1}^2] = E[x_{n-2}^2] = \cdots .$$

The variance of y_{n-1} is given by

$$\sigma_{y_o}^2 = E[y_o^2] - E[y_o]^2$$

$$= \frac{1-a}{1+a} E[x^2] - E[x]^2 .$$

The ratio $(1-a)/(1+a)$ is also the ratio of the unfiltered to filtered sample energies, so a reasonable value for y_o is a single unfiltered noise sample multiplied by the square root of this ratio.

The components of the filtered signal and noise samples are each computed using Eq. 9. After the last signal sample is used, the values of x_n in Eq. 9 for the signal components are zero while the filtered signal decays. Additional noise samples are generated and filtered during the signal decay, and the filtering process continues until the SNR for a filtered sample drops below the desired echo SNR divided by 10. At the end of the filtering process the program skips to the sample correlation and normalizing calculations.

The part of the program skipped above is used on runs where only the desired SNR is changed. This part is reached only if no changes were made in the fish school section or the sampling parameters. The signal and noise samples from the previous run are used, and a new noise gain is computed by NGAIN from the new desired SNR. The previous noise samples are multipled by the new gain factor and the program proceeds to the echo crosscorrelation calculations.

If the desired SNR is infinite, the crosscorrelations of the left-right and up-down echoes are computed using only the unnormalized signal samples in Eq. 2. For finite SNR's, the crosscorrelations are computed using unnormalized samples of signal plus noise. Next, the signal and noise samples are normalized by the square root of their respective echo energies. The echo crosscorrelations are normalized by the square root of the product of the energies of the two correlated echoes. Other values relating to the energy in each sample and to the summed energy of all fish contributing to each sample are also normalized. These values are used in estimating the down-range dimension of the school as described in Chapter 2.

The final part of the echo processing section is the calculation of the fish school location and dimension estimates. The normalized left-right and up-down crosscorrelations are used in computing the horizontal and vertical angular location and dimension estimates as described by Eq. 4. The down-range dimension estimate which is related to the sample energies is given by Eq. 5 or Eq. 21.

Data Storage and Print Sections

The results of the simulation are now stored on tape. Two tapes are used in order to minimize information retrieval time during further data processing. On the first tape, the complete data needed for future runs are stored, while on the second tape only the final spatial estimates, echo crosscorrelations, and echo energies are stored for use in analyzing and plotting the results.

The final section in SNGLPNG is the print section. During the execution of the previous sections, a summary of the input file data, tape storage parameters, and messages denoting the program flow are printed, but the results of the simulation are printed in this section. The results are divided into four parts. The print code supplied by the input data determines which parts will be printed. The first is a listing of the fish coordinates, their propagation delays, and their amplitude and Doppler characteristics. The second part is a listing of the normalized quadrature samples, the number of fish contributing to each sample, and the normalized energy density in each sample. The third part printed is a listing of the unnormalized signal and noise samples. The noise samples are always computed for future runs even though they aren't used when the desired SNR is infinite. The last part, which is always printed, contains a summary of the input data, the signal and noise energies, the echo crosscorrelations, and the dimension estimates computed from the ellipsoid dimensions, the fish coordinates, and the quadrature samples.

After leaving the print section, if results are desired for another SNR, the program skips back to the echo processing section and computes new results by changing only the gain of the noise. Otherwise, the program returns to the input section to begin on a new school.

CHAPTER 4

ANALYSIS AND RESULTS OF THE SIMULATIONS

Two general areas relating to the performance of the split-beam technique are studied using the simulations. Section 4.1 investigates the effect of adding uncorrelated noise to the target echo. Since the dimension estimates are calculated from the signal crosscorrelations, biases toward larger values are expected because of the decorrelating effect of the noise. Section 4.2 attempts to determine the relationship between the target, transmit pulse, and sampling parameters in estimating target characteristics. Fluctuations in these estimates, which are most noticeable when the signals are undersampled, are traced to terms in the crosscorrelation calculations.

Three sizes of schools at a range of 500 m are simulated. In the large school, the ellipsoid dimensions in the x', y', and z directions shown in Fig. 1, are set equal to 50 m, 75 m, and 25 m. In the middle size, they equal 25 m, 37.5 m, and 12.5 m, and in the small school, 10 m, 15 m, and 5 m.

Two shapes of transmit pulse envelopes are used. A 1 ms rectangular pulse envelope is compared with a 1.385 ms Hanning ($\sin^2$) pulse envelope. The Hanning pulse is chosen because its high-frequency energy spectrum is much lower when compared with the rectangular pulse.

The pulse length of the Hanning envelope is determined by equating the pulse resolutions defined by Eq. 11 for both shapes.

$$T \equiv \frac{\int_{-\infty}^{\infty} c_s^2(\tau)d\tau}{2\ c_s^2(0)}, \text{ where } c_s(\tau) = \int_{-\infty}^{\infty} s(t)s(t-\tau)dt\ . \tag{11}$$

For

$$s(t) = \begin{cases} 1 & 0 < t < 1\text{ ms} \\ 0 & \text{otherwise} \end{cases}$$

or

$$s(t) = \begin{cases} \sin^2 \frac{2\pi}{1.385}\, t & 0 < t < 1.385 \text{ ms} \\ 0 & \text{otherwise} \end{cases},$$

the value of the pulse resolution is $T = 0.333$ ms.

The sampling frequency is 5 kHz in most of the simulations. The bandwidth of the unfiltered noise samples, which is determined by the sampling frequency, is also equal to 5 kHz in most cases. The signal-plus-noise samples are then digitally filtered using a 1 kHz bandwidth.

Two sets of beam patterns are used in the simulations. The first set is described in Chapter 3 and Appendix E. The second set is also described in Appendix E, and its use is denoted by an asterisk in the simulation results.

4.1 Effects of Uncorrelated Noise

Some insight into the effect of adding uncorrelated noise is provided by analyzing the crosscorrelation of two signals plus noise from a single point target. The normalized echo crosscorrelation is given by

$$\tilde{C}_{1,2}(0) = \frac{\int_{-\infty}^{\infty}[\tilde{s}(t)+\tilde{n}_1(t)][\tilde{s}^*(t)\,e^{-j\theta}+\tilde{n}_2^*(t)]dt}{\left\{c_{1,1}(0)\cdot c_{2,2}(0)\right\}^{1/2}}, \tag{12}$$

where $c_{1,1}$ and $c_{2,2}$ are the unnormalized autocorrelations of the signals and are used to normalize the echo crosscorrelation, $\tilde{s}(t)$ is the complex return of the point echo, θ is the bearing to the target, and $\tilde{n}_1(t)$ and $\tilde{n}_2(t)$ are uncorrelated complex noise returns at centers 1 and 2. By defining

$$E_{S,S} = \int_{-\infty}^{\infty}\tilde{s}(t)\tilde{s}^*(t)dt \qquad E_{1,1} = \int_{-\infty}^{\infty}\tilde{n}_1(t)\tilde{n}_1^*(t)dt$$

$$E_{2,2} = \int_{-\infty}^{\infty}\tilde{n}_2(t)\tilde{n}_2^*(t)dt \qquad \tilde{E}_{S,1} = \int_{-\infty}^{\infty}\tilde{s}(t)\tilde{n}_1^*(t)dt$$

$$\tilde{E}_{S,2} = \int_{-\infty}^{\infty}\tilde{s}(t)\tilde{n}_2^*(t)dt \qquad \tilde{E}_{1,2} = \int_{-\infty}^{\infty}\tilde{n}_1(t)\tilde{n}_2^*(t)dt,$$

the crosscorrelation is expressed as

$$\tilde{C}_{1,2}(0) = \frac{E_{S,S}\,e^{-j\theta} + \tilde{E}_{S,2} + \tilde{E}_{S,1}^*e^{-j\theta} + \tilde{E}_{1,2}}{\sqrt{\left[\left(E_{S,S} + 2\,\mathrm{Re}\left\{\tilde{E}_{S,1}\right\} + E_{1,1}\right)\left(E_{S,S} + 2\,\mathrm{Re}\left\{e^{j\theta}\,\tilde{E}_{S,2}\right\} + E_{2,2}\right)\right]}}. \tag{13}$$

The noise terms $\tilde{n}_1(t)$ and $\tilde{n}_2(t)$ are assumed to be uncorrelated with the signal $\tilde{s}(t)$ and each other. These signals are band limited and, if their time-bandwidth product is much greater than unity, the magnitudes of $\tilde{E}_{S,1}$, $\tilde{E}_{S,2}$, and $\tilde{E}_{1,2}$ should be much less than $E_{S,S}$, $E_{1,1}$, or $E_{2,2}$.

Equation 13 can be expanded using the binomial theorem for both high and low signal-to-noise ratios. For the high SNR expansion, the terms involving uncorrelated factors are neglected and the crosscorrelation becomes

$$\tilde{C}_{1,2}(0) \approx e^{-j\theta}\left[1 - \frac{1}{SNR}\right], \tag{14}$$

where $E_{S,S} >> E_{1,1} \approx E_{2,2}$ and $SNR \approx E_{S,S}/[(E_{1,1} + E_{2,2})/2]$.

This equation shows that the location estimate, determined from θ, should remain unbiased over this range, but that the dimension estimate, obtained from $|\tilde{C}_{1,2}(0)|$, is a function of SNR^{-1}. This illustrates the decorrelating effect of the noise.

For the low SNR expansion, the terms involving uncorrelated factors are retained to illustrate the result when the $SNR \to 0$.

$$\tilde{C}_{1,2}(0) \approx e^{-j\theta}\left(SNR + \frac{\tilde{E}_{S,1}^{*}}{\sqrt{E_{1,1}E_{2,2}}}\right) + \frac{\tilde{E}_{S,2}}{\sqrt{E_{1,1}E_{2,2}}} + \frac{\tilde{E}_{1,2}}{\sqrt{E_{1,1}E_{2,2}}}, \tag{15}$$

where $E_{1,1} \approx E_{2,2} >> E_{S,S}$.

Equation 15 shows that if the SNR is much greater than the terms involving uncorrelated factors, which are small, the location estimate will remain unbiased; however, the dimension estimate is severely biased. As the SNR$\rightarrow$0, the remaining terms, which all have random angles, will cause the location and dimension estimates to fluctuate randomly from ping to ping.

The results of the simulations for the three school sizes agree with the single point analysis, as is illustrated in Figs. 7 through 10. All three schools are located at a horizontal bearing of 12.5°. The numbers of fish in each school were chosen so that approximately the same number of fish contribute to a given sample for all school sizes. Figure 7 shows the mean horizontal bearing to the schools versus SNR for 30 simulated pings on 30 independently generated schools, for each school size. Figure 8 shows the standard deviations of these estimates versus SNR over the 30 pings. These figures show that the location estimates remain unbiased and have fairly low standard deviations down to SNR's of approximately -5 dB.

Figures 9 and 10 show the relationship between the horizontal dimension estimates and the SNR for the three school sizes. Each dimension estimate becomes biased from its actual value as SNR decreases, and each asymptotically approaches the slope predicted by Eq. 14 for a single point target.

The down-range dimension estimates are not computed from the echo crosscorrelations. Instead, they.are derived from the approximate radial density function using the normalized energies of the

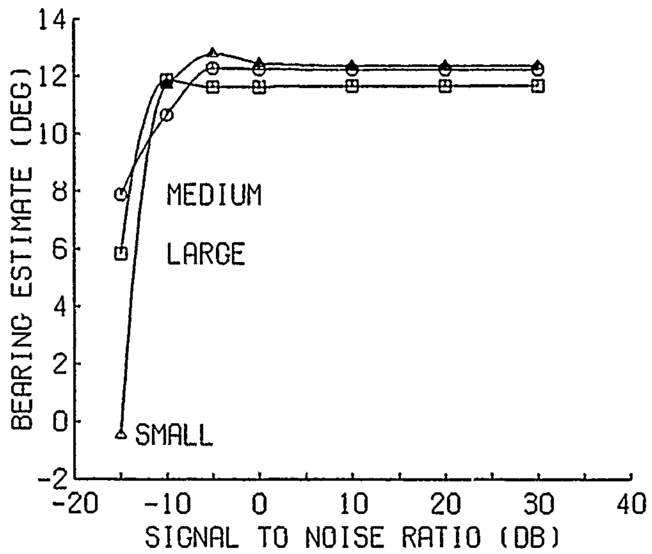


Figure 7. Illustration of the effect of uncorrelated noise on the horizontal bearing estimate (actual bearing = 12.5°).

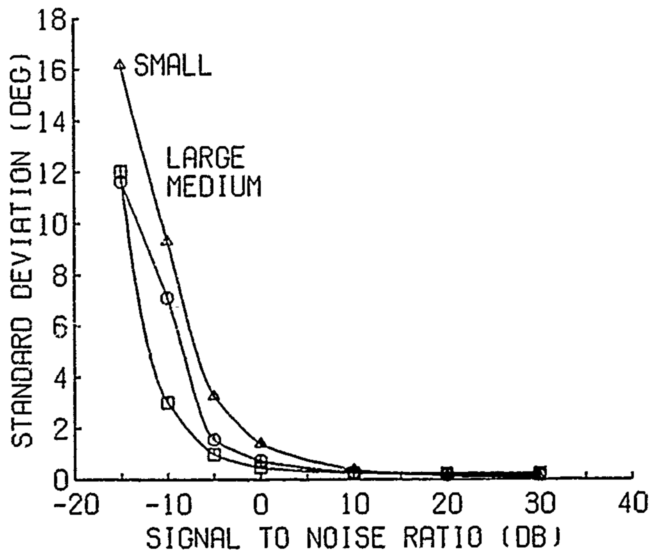


Figure 8. Illustration of the stability of the horizontal bearing estimate versus uncorrelated noise.

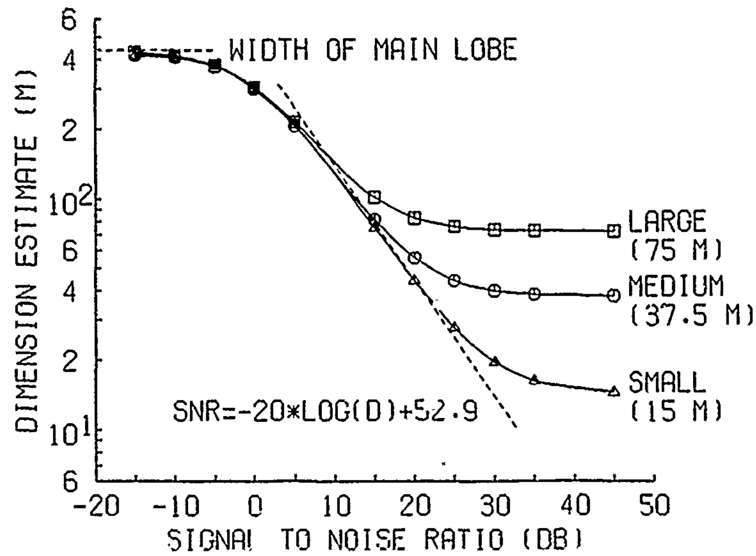


Figure 9. Illustration of biases in horizontal dimension estimates caused by uncorrelated noise (actual values are in parentheses).

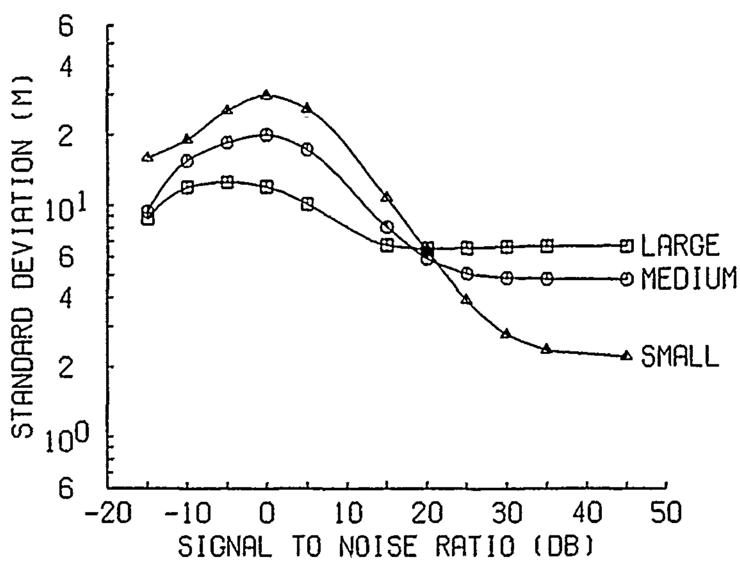


Figure 10. Illustration of the fluctuations in the horizontal dimension estimates caused by uncorrelated noise.

echo samples as described in Appendix C. The normalization reduces the effect of additive noise on the dimension estimates and the biases seen in the horizontal and vertical estimates aren't observed in the down-range estimates. Noise should change the shape of the density function, tending to reduce its peak and make the density more uniform. The value of D for a uniform density function $P_R(r) = 1/2$ for $-1<r<1$ and zero otherwise is

$$D = \left[\int_{-1}^{1} (1/2)^2 \, dr\right]^{-1} = 2 ,$$

which is the actual width of the distribution. Because the value of D for the density function corresponding to an ellipsoid is $(5/6)\cdot 2$, an increase of 1/6 is expected in the simulations. This increase can be seen in Fig. 11.

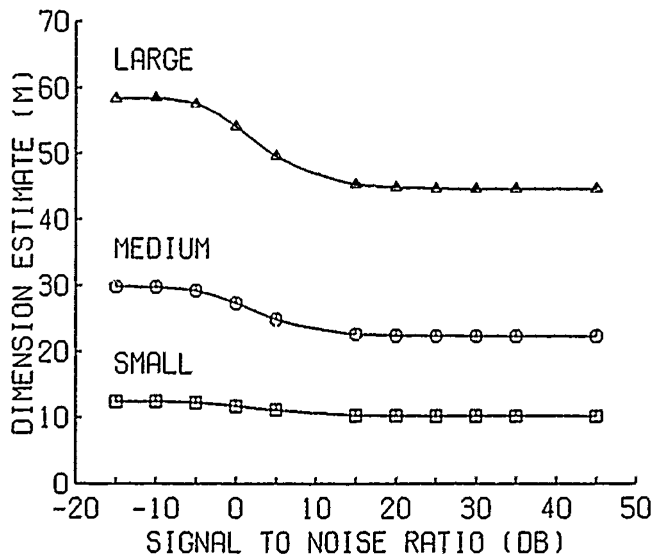


Figure 11. Effect of noise on the down-range dimension estimate.

In the simulation, the beginning and end of the school is known; however, in an actual system, the length of the echo is determined by thresholds. Ping-to-ping fluctuations in the value of D_{DR} will increase with decreasing SNR as the echo becomes harder to detect.

4.2 Sources of Fluctuations in the Spatial Estimates

The intent of this portion of the study is to identify some of the parameters that affect the performance of the split-beam system. Ping-to-ping fluctuations in the dimension estimates can be traced to fluctuations in the terms of Eqs. 1 and 2. In addition to the random aspects of each fish echo, the terms in Eq. 1 are determined by the school size and density and the transmit pulse. The terms in Eq. 2 are determined by the school's down-range dimension and the sampling frequency. For certain combinations of these parameters, larger fluctuations in the dimension estimates are noticed.

To better understand the possible sources of the fluctuations, it is helpful to expand one term of Eq. 2 as a function of the individual fish echoes. Initially we shall assume that the same fish contribute to both samples, and their echo amplitudes are also the same for both samples. The resulting expansion for n fish is

$$Z_L Z_R^* = \left[a_1 e^{j\phi_1} + \cdots + a_n e^{j\phi_n}\right]\left[a_1 e^{-j(\phi_1-\Delta_1)} + \cdots + a_n e^{-j(\phi_n-\Delta_n)}\right]$$
$$= a_1^2\, e^{j\Delta_1} + \cdots + a_n^2\, e^{j\Delta_n} + a_1 a_n e^{j(\phi_1-\phi_n+\Delta_n)} + a_1 a_n e^{-j(\phi_1-\phi_n-\Delta_1)} \qquad (16)$$
$$+ \ (n^2-n-2 \text{ terms involving other possible pairs of fish echoes})$$

where "a" represents the echo amplitude, Δ represents the phase difference between the right and left echo determined by the angular position of the fish, and ϕ represents a random angle determined by the left signal propagation delay to each random location. The sum of the terms in the form $a^2e^{j\Delta}$ has a phase angle bounded by the angular extent of the school, since Δ represents the angular position of each fish. The next two terms represent phasors whose angles are random. More random phasors result from the other pairs of fish echoes. If the number of fish in the samples is large, these random phasors should have a small mean expected value. However, when only a few random phasors are added to a similar number of phasors within the school boundaries, the angle of the product $Z_L Z_R^*$ may lie outside the school boundary. This will decrease the magnitude of the left-right crosscorrelation and produce an abnormally large dimension estimate.

Now we consider the case where the echo amplitudes are not slowly varying with time, and the left and right echo amplitudes of a fish at the time of the sample may differ. This will occur for samples taken near the edges of a fish echo. If, for example, the amplitude of the right echo for the first fish is zero, then the terms $a_1^2 e^{j\Delta_1}$ and $a_1 a_n e^{-j(\theta_1-\theta_n-\Delta_1)}$ in Eq. 16 are zero. For small numbers of fish, the loss of a random phasor will tend to increase the fluctuations.

Simulation results comparing the horizontal dimension estimates for schools of varying densities are shown in Table 1. The trend toward higher standard deviations for lower fish densities is caused by the occasional occurrence of abnormally large estimates as high as 40 m for the small school. Using a Hanning pulse whose amplitude envelope is slowly varying, the fluctuations are smaller than for the rectangular pulse, although the trend toward increased fluctuations for decreasing densities is still noticed. The results of increasing the sampling rate compared with changing the pulse shape are shown in Table 2. If the number of samples per pulse length is increased while using a rectangular pulse, the fluctuations caused by samples taken near the edge of the fish echo should be reduced by more good samples taken well within the edges of the echo.

The above discussion suggests that the maximum bandwidth of the transmit pulse or received signals prior to the onset of undesirable fluctuations is determined by the spatial characteristics

Table 1. Illustration of dimension estimate fluctuations versus fish school density and transmit pulse shape. Results are for 30 pings on independent schools.

Simulation Parameters	Number of Fish	Mean Horizontal Dimension, D_H (m)	Standard Deviation, σ_{DH} (m)
Small school*	500	15.57	3.58
No random amplitudes No Doppler shifts	250	14.90	2.50
Rectangular pulse	100	15.36	5.66
	50	13.30	2.10
	25	16.88	8.99
	10	14.61	7.53
Small school*	100	14.28	2.21
Random amplitudes Random Doppler shifts	50	13.69	2.76
Hanning pulse	25	13.60	3.62
	10	12.21	4.54
Large school*	500	73.14	5.78
No random amplitudes No Doppler shifts	250	72.54	5.23**
Rectangular pulse	125	74.27	6.04
	50	71.86	13.01

Sampling frequency = 5 kHz
School locations: $\psi = 0$, range = 500 m
SNR = infinity

*Alternate beam amplitude corrections used
**Statistics based on 17 pings

Table 2. Illustration of the reduction in relative dimension estimate fluctuations for larger school sizes (x' dimension) versus transmit pulse length. Results are for 30 pings on independent schools for each school size.

Transmit Pulse	Mean Horizontal Dimension Estimate, D_H (m)	Standard Deviation, σ_{D_H} (m)	Sampling Frequency (kHz)
Rectangular* 1 ms	15.36	5.66	5
	14.78	3.27	25
Hanning* ($\sin^2$) 1.385 ms	13.78	2.41	5

School size: small (10 m, 15 m, 5 m), 100 fish
School location: $\psi = 0°$, range 500 m
No random amplitudes and Doppler shifts assigned to scatterers
SNR = infinity

*Alternate beam amplitude corrections used

of the transducer. The rise time of the echo amplitude must be long compared to the maximum difference in the arrival times of a fish echo at the left and right halves. If we choose the rise time to be ten times the maximum difference, the relationship is given by

$$\frac{\Delta\tau}{10} = \frac{SH}{1500} \sin\theta_{max} ,$$

where $\Delta\tau$ is the 100% rise time of the echo, SH is the horizontal separation of the transducer halves shown in Fig. 6, and θ_{max} is the maximum practical angle in the main lobe for receiving a fish echo. If the value of $\theta_{max} = 15°$, then $\Delta\tau = 0.098$ ms and the bandwidth of the signal should be less than $1/\Delta\tau$, or 10 kHz. Using this bandwidth, the sampling rate is determined only by the desired number of samples in the total echo.

Equation 16 can also be used to illustrate the effect of including random amplitudes and Doppler shifts on the dimension estimate fluctuations. The random Doppler shifts can be included in Δ by redefining Δ as

$$\Delta = \frac{2\pi}{c}\,(f_o + f_d)\,\sin\theta \ ,$$

where f_d is the Doppler shift. If $f_o = 30$ kHz and the largest value of f_d is 100 Hz, then the change in Δ caused by f_d is negligible and should not affect the dimension estimates.

The effect of the random amplitudes is illustrated by comparing the expected amplitudes of the random phasors for the equal amplitude and random amplitude cases. When the amplitudes are Rayleigh distributed random variables, the parameter α of the distribution can be determined by normalizing the expected echo energies in the two cases. For the equal amplitude case, using a rectangular pulse and neglecting beam amplitude corrections, the expected echo energy is given by

$$k \sum_{i=1}^{N} A_i^2 = k\,N \ ,$$

where k is the number of samples per pulse length and $A_i = 1$ for all fish. For the Rayleigh distributed amplitudes, the expected echo energy is

$$k \sum_{i=1}^{N} A_i^2 = k\, NE\left[A_i^2\right] = k\,N\,2\alpha^2 .$$

Equating the two expected energies results in $\alpha = 1/\sqrt{2}$.

The ratio of the normalized amplitudes of the random phasors is given by

$$\frac{E[a_i a_j]}{E[1 \cdot 1]} = E[a_i]\; E[a_j] = \left(\alpha\sqrt{\frac{\pi}{2}}\right)^2 = \frac{\pi}{4} .$$

The fluctuation in the crosscorrelation caused by these random phasors should be reduced for the random amplitude case by approximately this value.

Since the dimension estimates are a function of the square root of the crosscorrelation, their fluctuations should be reduced by approximately $\sqrt{\pi/4}$. This reduction should be statistically insignificant for the simulations shown in Table 3 if the estimates are assumed to be normally distributed.

If it is assumed that the 30 dimension estimates are normally distributed, an approximate value for the variance in the dimension fluctuations can be computed. The expected sample variance is defined as

$$E[\bar{v}] = \frac{29}{30}\,\sigma^2 .$$

$\overline{v}$ is a chi-square statistic with 29 degrees of freedom,[1] and the corresponding fluctuation in the sample variance, $\sigma^2_{\overline{v}}$, is

$$(2\cdot 29)/(30^2)\ \sigma^4 \ .$$

A typical value of $\overline{v}$ for the small school is 9 m^2, and the corresponding value of $\sigma_{\overline{v}}$ is 2.4 m^2. These fluctuations are greater than the reduction of $\sqrt{\pi/4}$ caused by random amplitudes.

Table 3. Illustration of the effect of ascribing random amplitudes and Doppler shifts to the point scatterers.

	Equal Amplitudes No Doppler Shifts		Random Amplitudes and Doppler Shifts	
School Size	Mean Horizontal Dimension, D_H (m)	Standard Deviation, σ_{DH} (m)	Mean Horizontal Dimension, D_H (m)	Standard Deviation, σ_{DH} (m)
Small* (25 fish)	15.38	3.35	13.60	3.62
Small* (100 fish)	13.79	2.41	14.28	2.21
Medium (250 fish)	36.33	4.27	37.72	4.61

Transmit pulse: 1.385 ms Hanning
Sampling frequency: 5 kHz
School location: $\psi = 0$, range = 500 m
SNR = infinity

*Alternate beam amplitude corrections used

Another effect on the dimension estimates is the expected reduction in fluctuations as the pulse length is shortened, because higher pulse resolution provides more statistically independent echo samples.[2] However, if the pulse length is shortened to the point where only a few fish contribute to each sample, then fluctuations will increase as described earlier. Simulation results for pulse lengths where the typical number of fish per sample is greater than 10 are shown in Table 4. These results illustrate the reduction in relative fluctuations for lower ratios of pulse resolution to down-range size of the school. The relative fluctuations are the standard deviations divided by the actual horizontal dimension.

The distinction between single and multiple-fish targets can be accomplished using the ping-to-ping fluctuations in the cross-correlations. If two fish are used in Eq. 16, then two phasors pointing in the direction of the fish will be added to two random phasors. If the separation between the fish, denoted as Δ_1-Δ_2, is small, then the two random phasors of equal magnitude will be in nearly opposite directions and very little fluctuation will be noticed. However, as the separation increases, the random phasors will not cancel and fluctuations will result. A single fish will result in no fluctuations, since no random phasors are involved. Thus the detection of a single fish at a given range can only be accomplished in situations where the fish are separated by an amount sufficient to generate detectable fluctuations.

Table 4. Illustration of high standard deviations of dimension estimates for a rectangular transmit pulse and low sampling frequency.

School Size	Mean Horizontal Dimension, D_H (m)	Relative Standard Deviation, σ_{D_H} / D_H	School Size in x' Dimension (m)
Small*	14.28	0.155	10
Medium	37.72	0.122	25
Large*	72.20	0.090	50

Transmit pulse envelope: 1.385 ms Hanning ($\sin^2$)
Sampling frequency: 5 kHz
School location: $\psi = 0$, range = 500 m
Includes random amplitudes and Doppler shifts for scatterers
SNR = infinity
Number of fish: small, 100; medium, 250; large, 500

*Alternate beam amplitude corrections used

REFERENCES

1. A. Papoulis, Probability, Random Variables, and Stochastic Processes, McGraw-Hill Book Company, New York, N.Y., 1965.

2. W.A. Gardner and D.R. Jackson, "Extraction of Spatial and Temporal Parameters of a Body of Scatterers Using Cross-correlation," in preparation.

CHAPTER 5

CONCLUSIONS

Computer simulations of the split-beam method show that this technique should be useful in estimating the spatial characteristics of fish schools. The dimension estimates, however, are biased by noise such that for low signal-to-noise ratios the dimensions are irretrievable. For example, with a 30 dB signal-to-noise ratio, schools as small as 15 m can be estimated at a range of 500 m; however, with a 10 dB ratio, the minimum estimate obtainable is approximately 80 m. Thus all schools with dimensions of around 80 m or less would have the same dimension estimate at this signal-to-noise ratio. The location estimates are not biased by noise, and useful location information should be obtainable for signal-to-noise ratios down to -5 dB.

Ping-to-ping fluctuations in the spatial estimates are reasonably small for sampling frequencies above the Nyquist rate and for high signal-to-noise ratios. These fluctuations decrease relative to the school size, as the ratio of pulse resolution to down-range extent of the school decreases. Typical results give standard deviations of approximately 2.5 m for the 15 m school and 6 m for the 75 m school. No changes in the magnitude of the fluctuations are noticed when random amplitude and Doppler shifts are added to the point scatterers. A small reduction in the fluctuations is expected for the addition of random amplitudes, but the sample size of 30 pings is not large enough for the change to be noticeable.

A beneficial use of the fluctuations is in the detection of single fish. This can be accomplished if the fish in a given range window are separated by the angular distance necessary to produce detectable fluctuations. The situation will still exist where two smaller fish that are close together will be indistinguishable from a larger fish.

Undersampling can create larger fluctuations for certain combinations of the target size and density, the bandwidth of the transmit pulse, and the sampling characteristics. These fluctuations are caused by random terms in the crosscorrelation calculations, and can be minimized by reducing the magnitudes of these random phasors and including enough of them that the effect of their sum is small. This involves increasing the number of fish per sample and decreasing the sample time-bandwidth product.

This thesis is a basic study of the factors affecting split-beam spatial estimates. It should provide useful information for actual split-beam measurements and implementations of the split-beam technique in larger simulation programs. Suggestions for further research involve analyzing actual split-beam data in an attempt to isolate the effects studied here.

LIST OF REFERENCES

T.J. Carlson and D.R. Jackson, "Empirical Evaluation of the Feasibility of Split Beam Methods for Direct In Situ Target Strength Measurement of Single Fish," APL-UW 8006, Applied Physics Laboratory, University of Washington, January 1980.

W.A. Gardner and D.R. Jackson, "Extraction of Spatial and Temporal Parameters of a Body of Scatterers Using Cross-correlation," in preparation.

G.C. Goddard and U.G. Welsby, "Statistical Measurement of the Acoustic Target Strength of Live Fish," Departmental Memorandum No. 456, Department of Electronic and Electrical Engineering, University of Birmingham, January 1975.

D.R. Jackson and G.L. Thomas, "Acoustic Measurement of Fish Schools Using Array Phase Information" (abstract), OCEANS '79, IEEE Publ. No. 78CH1478-7 OEC, September 1979, p. 59.

D.W. Lytle and D.R. Maxwell, "Hydroacoustic Estimation in High Density Fish Schools," Proc. Conf. Acoustics in Fisheries, Hull College of Higher Education, Hull, England, 26 and 27 September 1978.

A. Papoulis, Probability, Random Variables, and Stochastic Processes, McGraw-Hill Book Company, New York, N.Y., 1965.

R.J. Vent, I.E. Davies, R.W. Townsen, and J.C. Brown, "Fish School Target Strength and Doppler Measurements," Report No. NUC-TP-521, Naval Undersea Center, San Diego, California, July 1976.

APPENDIX A

DERIVATION OF SPATIAL ESTIMATES FOR NONOVERLAPPING ECHOES

In this appendix, the expressions for the angular location and dimension estimates are derived for the case where a rectangular transmit pulse is used and the individual fish echoes do not overlap. In this case either one or no fish contribute to each quadrature sample summation in Eq. 1. Correspondingly, each non-zero term in the summations of Eq. 2 can be expresssed as $|Z_i|^2 e^{j\phi_i}$, where Z_i is the normalized magnitude of the single fish echo present at time t_i, and ϕ_i is the angular position of that fish in electrical degrees. The summations in Eq. 2 over all samples can be expressed as summations over all fish by knowing the number of samples per fish echo.

$$\tilde{C}_{LR} = \sum_i \left|Z_i\right|^2 e^{j\phi_i} = k \sum_n \left|Z_n\right|^2 e^{j\phi_n} \tag{17}$$

where i is summed over all quadrature samples, n is summed over all fish, and $k = f_s \times$ the transmit pulse length.

Now, we define the mean and variance of the distribution of angles that are weighted by the fish sample energies as

$$\overline{\phi} = \frac{\sum_n \left|Z_n\right|^2 \phi_n}{\sum_n \left|Z_n\right|^2} \quad \text{and} \quad \sigma_\phi^2 = \frac{\sum_n \left|Z_n\right|^2 (\phi_n - \overline{\phi})^2}{\sum_n \left|Z_n\right|^2} \; . \tag{18}$$

If the fish are concentrated around the mean angle, $\overline{\phi}$,

$$\sigma_n = \phi_n - \overline{\phi} << 1 \qquad \text{and} \qquad \sigma_\phi^2 = \frac{\sum_n |Z_n|^2 \sigma_n^2}{\sum |Z_n|^2} \quad . \tag{19}$$

Using the Taylor series expansion, the crosscorrelation becomes

$$\tilde{C}_{LR} = k\ e^{j\overline{\phi}} \sum_n |Z_n|^2\ e^{j\sigma_n}$$

$$\approx k\ e^{j\overline{\phi}} \sum_n |Z_n|^2\ (1+j\sigma_n - \frac{\sigma_n^2}{2}) \ .$$

The values of Z_i from Eq. 17 are normalized, so by definition

$$\sum_i |Z_i|^2 = k \sum_n |Z_n|^2 = 1.$$

From Eq. 19, we have

$$\frac{\sum_n |Z_n|^2 \sigma_n}{\sum_n |Z_n|^2} = \frac{\sum_n |Z_n|^2 \phi_n}{\sum_n |Z_n|^2} - \frac{\sum_n |Z_n|^2 \overline{\phi}}{\sum_n |Z_n|^2} = 0 \ .$$

Thus $\sum_n |Z_n|^2 \sigma_n = 0$, and the crosscorrelation is

$$\tilde{C}_{LR} = e^{j\overline{\phi}}\ (1 - \frac{1}{2}\sigma_\phi^2\ ) \ .$$

The conversion from electrical to mechanical degrees is accomplished by using the transducer's spatial characteristics. Figure 12 shows the transducer halves separated by SH and a target located by r and θ. If r >> SH and θ is small, the difference in path lengths to each half is SH $\sin\theta \approx$ SH θ. The electrical difference in radians is $\phi \approx \frac{\omega_0}{c}$ SH $\theta = \gamma_H \theta$, where $\gamma_H = \frac{\omega_0}{c}$ SH is the conversion from mechanical to electrical degrees.

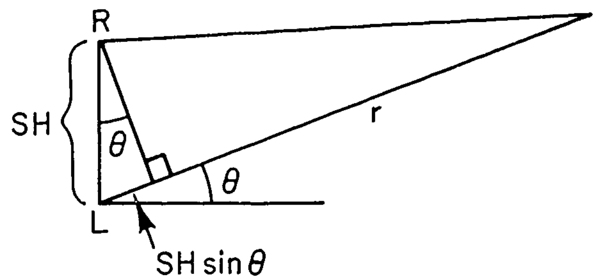


Figure 12. Conversion from mechanical to electrical degrees.

In mechanical degrees, the crosscorrelation is

$$\tilde{C}_{LR} = e^{j\gamma_H \overline{\theta}} \left(1 - \frac{1}{2} \gamma_H^2 \sigma_\theta^2\right) .$$

The expression for the mean horizontal angular position of the fish is

$$\overline{\theta}_H = \frac{1}{\gamma_H} \tan^{-1} \left\{ \frac{\mathrm{Im}\, \tilde{C}_{LR}}{\mathrm{Re}\, \tilde{C}_{LR}} \right\}$$

and the horizontal dimension of the school is given by

$$D_H = \sigma_\theta \cdot R \cdot F = \frac{\sqrt{2}}{\gamma_H} \sqrt{1 - \left|\tilde{C}_{LR}\right|}\; R \cdot F ,$$

where F is the conversion from the standard deviation of a distribution to the actual dimension of the distribution.

The vertical angular location and dimension estimates are given by

$$\overline{\theta}_V = \frac{1}{\gamma_V} \tan^{-1} \left\{ \frac{\mathrm{Im}\ \tilde{C}_{UD}}{\mathrm{Re}\ \tilde{C}_{UD}} \right\}$$

and

$$D_V = \frac{\sqrt{2}}{\gamma_V} = \sqrt{1 - |\tilde{C}_{UD}|}\ R \cdot F ,$$

where

$$\gamma_V = \frac{\omega_o}{c}\ SV$$

and SV is the separation between the vertical transducer halves.

APPENDIX B

RELATIONSHIPS BETWEEN THE SCHOOL DIMENSIONS AND THE STANDARD DEVIATION OF THE FISH LOCATIONS

In this appendix, the factor is calculated to convert the standard deviation of a distribution of scatterers to the actual size of the group. The simulation uses an ellipsoid filled with scatterers whose locations are independent and uniformly distributed. The standard deviation of this distribution of scatterers is computed here.

Since the density of scatterers is uniform throughout the ellipsoid, the probability density function (PDF) of the scatterers is equal to the normalized cross-sectional area. For an ellipsoid defined by

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 ,$$

the cross-sectional area parallel to the x-z plane, for example, is given by

$$A(y) = \pi ac \left[1 - (y/b)^2\right] \qquad -b \le y \le b .$$

The normalizing factor is given by

$$\int_{-b}^{b} A(y)\, dy = 4/3\,\pi\, abc$$

and the PDF is expressed as

$$P_y(y) = \frac{\pi ac[1-(y/b)^2]}{4/3\,\pi\, abc} = \frac{3(b^2-y^2)}{4b^3} .$$

The variance in the y dimension is given by

$$\sigma_y^2 = E\{y^2\} - E\{y\}^2 = \int_{-b}^{b} y^2 \, \frac{3(b^2-y^2)}{4\,b^3} \, dy - 0 = \frac{b^2}{5} \quad .$$

So the relationship between the actual dimension, 2b, and the standard deviation, σ_y, is

$$2b = 2\,\sqrt{5}\;\sigma_y = F\,\sigma_y \qquad \text{and} \qquad F = 2\,\sqrt{5}\ .$$

APPENDIX C

DERIVATION OF THE DOWN-RANGE DIMENSION ESTIMATE

The down-range dimension estimate, D_{DR}, is calculated using the definitions

$$D = \frac{1}{\int_0^{\infty} P_R(r)^2 \, dr}$$

and

$$D_{DR} = 6/5 \; D \; , \tag{20}$$

where $P_R(r)$ is the radial density function of the fish. If the density function for a uniformly filled ellipsoid, described by $x^2 + y^2/b^2 + z^2/c^2 = 1$, is used to compute D_{DR}, the value differs from the actual down-range width of the ellipsoid. For this case,

$$P_X(x) = \frac{\pi b\sqrt{1-x^2}\; c\sqrt{1-x^2}}{4/3\pi bc} = \frac{3(1-x^2)}{4}$$

$$D = \left(\int_{-1}^{1} P_X(x)^2 dx\right)^{-1} = \left(\frac{9}{16}\int_{-1}^{1} (1-x^2)^2\, dx\right)^{-1} = \frac{5}{3} \; .$$

Since the actual dimension equals 2, the correction factor of 6/5 in Eq. 20 is needed for the ellipsoids used in the simulations.

Two methods of approximating the radial density function are used in the simulation. Both involve energies associated with each quadrature sample. The first method forms the density function from the normalized energy of the samples.

The result in terms of samples is

$$P(i) \approx \frac{|Z(i)|^2}{\sum_i |Z(i)|^2 \Delta} ,$$

and the value of the down-range dimension is

$$D_{DR} \approx 6/5 \frac{\left(\sum_i |Z(i)|^2\right)^2 \Delta^2}{\sum_i |Z(i)|^4 \Delta} = \frac{1800}{f_s} \frac{\left(\sum_i |Z(i)|^2\right)^2}{\sum_i |Z(i)|^4} ,$$

where

$$\Delta = \frac{1500}{f_s} = (m/smpl) .$$

The second method forms the density function by neglecting the phase of the fish echoes and summing the energy magnitudes of all contributing fish echoes. These sums are also normalized, and the density function is given by

$$P(i) = \frac{\sum_k \left(A_i(k) \ B(k)\right)^2}{\sum_i \left(\sum_k A_i(k) \ B(k)\right)^2 \Delta} ,$$

where the notation of Eq. 1 is followed. The down-range dimension estimate is then given by

$$D_{DR} = \frac{\left[\sum\limits_i \sum\limits_k \left(A_i(k) \;\; B(k)\right)^2 \Delta\right]^2 \cdot \frac{6}{5}}{\sum\limits_i \left[\sum\limits_k \left(A_i(k) \;\; B(k)\right)^2\right]^2 \Delta}$$

$$= \frac{1800}{f_s} \frac{\left[\sum\limits_i \sum\limits_k \left(A_i(k) \;\; B(k)\right)^2\right]^2}{\sum\limits_i \left[\sum\limits_k \left(A_i(k) \;\; B(k)\right)^2\right]^2} \; . \tag{21}$$

APPENDIX D

LISTINGS OF COMPUTER PROGRAMS

This appendix provides listings of the programs used in the simulations. The first listing is the program EFILL which generates the random locations of the point scatterers. The second listing is of the main program SNGLPNG.

Table 5. Listing of EFILL

```
      PROGRAM EFILL(INPUT,OUTPUT,TAPE1,TAPE5=INPUT,TAPE6=OUTPUT)
C   THIS PROGRAM CREATES AN INITIAL FILE FOR THE PROGRAM SNGLPNG.
C   THE FILE CONTAINS N FISH LOCATIONS INSIDE AN ELLIPSOID WITH
C   X,Y, AND Z DIMENSIONS OF 2*A,2*B, AND 2*C METERS.  SPACE FOR
C   OTHER DATA USED BY SNGLPNG BUT NOT COMPUTED HERE, IS FILLED
C   WITH ZEROES.
        READ(5,500) N,A,B,C
  500       FORMAT(I5,5X,3F10.0)
        DATA (NF1(I),I=2,3),(RMS(I),I=1,500),(DUM6(I),I=1,6),
     *      (DUM29(I),I=1,29),(DUM8(I),I=1,8)/-1,-1,500*1.,43*0/
        DATA (DUM500(I),I=1,500)/500*0/
        J=1
        READ(5,501) NF1(1)
        CALL RANSET(NF1(1))
        DO 100 I=1,200
  100   DUMP=RANF(1.)
      GOTO 20
   10 READ(5,501) NF1(1)
  501     FORMAT(I3)
      IF(EOF(5).NE.0.) 999,20
   20 WRITE(1) NF1,DUM6,DUM6,DUM6,DUM6
      WRITE(1) DUM29
      WRITE(6,600) (NF1(I),I=1,3),N,A,B,C
  600     FORMAT(///,1X,*RANDOM FILLING OF ELLIPSOID AND TAPE GENERATION*
     *    ///3X,*SCHOOL NUMBER =*,I3,2I2,10X,
     *    //3X,*NUMBER OF FISH =*,I6,/3X,
     *    *A(X AXIS) =*,F10.2,5X,*B(Y AXIS) =*,F10.2,5X,*C(Z AXIS) =*,
     *    F10.2,//5X,*NO.*,6X,*X*,9X,*Y*,9X,*Z*,//)
      DO 200 I=1,N
   90       O=2.*(RANF(0.)-.5)
            P=2.*(RANF(0.)-.5)
            Q=2.*(RANF(0.)-.5)
            TEST=O**2+P**2+Q**2
        IF(TEST.GT.1.) GOTO 90
       X(I)=A*O
       Y(I)=B*P
       Z(I)=C*Q
  200 WRITE(6,610) I,X(I),Y(I),Z(I)
  610     FORMAT(1X,I6,3F10.2)
      IF(N.GE.500) GOTO 190
      K=N+1
      DO 195 I=K,500
  195 X(I)=Y(I)=Z(I)=0.
  190 WRITE(1  X,Y,Z,DUM500,DUM500,DUM500,DUM500,DUM500,DUM500,
     *    RMS,DUM500,DUM500,DUM500,DUM500
      J=J+1
      IF(J.GT.30) GOTO 999
      GOTO 10
  999 STOP
      END
```

Table 6. Listing of SNGLPNG

```
      PROGRAM SNGLPNG(INPUT,OUTPUT,TAPE1,TAPE2,TAPE4,TAPE5=INPUT,
     *   TAPE6=OUTPUT)
C***********************************************************************
C                                                                      *
C          THIS PROGRAM SIMULATES A SINGLE PING ON A FISH SCHOOL       *
C          AND CALCULATES THE SCHOOL'S LOCATION AND DIMENSION          *
C          ESTIMATES USING THE SPLIT-BEAM METHOD.  THE PROGRAM         *
C          REQUIRES TWO INPUT FILES:                                   *
C               INPUT FILE - DESIRED PARAMETERS FOR THIS RUN           *
C               TAPE1      - RESULTS FROM A PREVIOUS RUN OR FROM       *
C                            THE PROGRAM EFILL                         *
C          AND PROVIDES TWO BINARY OUTPUT FILES:                       *
C               TAPE2 - COMPLETE RESULTS FOR USE IN FUTURE RUNS        *
C               TAPE4 - SUMMARY OF RESULTS FOR DATA ANALYSIS.          *
C                                                                      *
C          FURTHER INFORMATION IS GIVEN IN SEPERATE DOCUMENTATION.     *
C                                                                      *
C***********************************************************************
      DIMENSION AMP(500),ASNR(4),ASNR1(4),BCL(500),BCU(500),DHQ(2),
     *   DRQ(2),EFL(500),EFU(500),ES(4),EN(4),EQ(4),ESN(4),ENN(4),EQN(4)
     *   ,ESS(500,4),RMS(500),NF(3),NP(3),NS(4),NSEED(99),NF1(3),NS1(4),
     *   NPW(100),Q(100,4,2),QS(100,4,2),QN(100,4,2),SSNR(100,4),
     *   SDQ(100,4),SDA(100,2),SF(100),T(500,4),W(4),X(500),X2(4),
     *   Y(500),Z(500),DVQ(2),DQ(4),SDAN(100,2),DSN(8)
      COMMON /PLSE/PW,F0,DP(500)/ANGL/A,A2,B2,PI
C  CONSTANTS AND INITIAL VALUE
        IR=1
        PI=3.141592654
        TWOPI=2.*PI
        CW=1500.
        RADEG=57.2957795131
        SR2=SQRT(2.)
        SR5=2*SQRT(5.)
C
C ***INPUT SECTION***
C
C   TABLE OF 99 RANDOM SEEDS
      READ(5,5010) (NSEED(I),I=1,99)
 5010    FORMAT(8F10.8)
C
C *DESIRED SNR VALUES FOR ADDITIONAL RUNS*
C
      READ(5,5011) ISNRM,(DSN(I),I=1,8)
 5011    FORMAT(I1,3X,8F10.0)
C    NUMBER OF RPINGS FOR THIS RUN
      READ(5,5012) IRM
 5012    FORMAT(I5)
C
C   DESIRED PARAMETERS FROM INPUT FILE
C
   10 ISNR=NW=0
      READ(5,5000) NF,N,A,B,C,THD,BEAR,DS,DT,R,RMSE,
     *   NS,FOP,PWP,FSP,DSNR,BW,EEES
 5000    FORMAT(I3,2I2,3X,I4,6X,6F10.0,/,3F10.0,4I2,2X,4F10.0,/,2F10.0)
      IF(EOF(5).NE.0.) 999,15
```

```
   15 WRITE(6,6000) NF,N,A,B,C,THD,BEAR,DS,DT,R,RMSE,
     *    NS,FOP,PWP,FSP,DSNR,BW,EEES
 6000    FORMAT(1H1,1X,*SINGLE RUN INFORMATION*,//3X,*SCHOOL NUMBER =*,
     *    I3,2I2,3X,*(N,A,B,C (I4) : AMP (I2) : DOPP (I2))*,
     *    /5X,*N =*,I5,3X,*A =*,F6.1,3X,*B =*,F6.1,3X,*C =*,F6.1,
     *    3X,*ASPECT =*,F5.1,3X,*BEARING =*,F5.1,/5X,*DS =*,F7.1,3X,
     *    *DT =*,F5.1,3X,*R =*,F7.1,3X,*MSE =*,F7.3,//3X,*SAMPLE *,
     *    *PROCESSING NUMBER = *,4I2,3X,*(FO,PW,FS (I2) : FLTR (I2) :*,
     *    * SNR (I2) : NSEED (I2))*,
     *    /5X,*FO =*,F6.1,3X,*PW =*,F7.3,3X,
     *    *FS =*,F7.3,3X,*D SNR =*,F6.1,3X,*BW =*,F7.1,3X,*EEES =*,F7.3)
      FO=FOP*1000.
      PW=PWP/1000.
      FS=FSP*1000.
      IF(BW.GT.FS/2.) GOTO 999
C  PRINT CODE
      READ(5,5005) NP
 5005    FORMAT(3I1)
C
C *PREVIOUS RUN PARAMETERS FROM TAPE STORAGE*
C
C       (READ UNTIL SCHOOL NUMBERS MATCH OR EOF)
   16 READ(1) NF1,THD1,BEAR1,DS1,DT1,R1,RMSE1,NS1,ASNR1,DSNR1,BW1,
     *    L,EEES1,VMN,RLTE,RLT1,VMX
      IF(EOF(1).NE.0.) GOTO 999
      WRITE(6,6001) NF1,THD1,BEAR1,DS1,DT1,R1,RMSE1,NS1,DSNR1,BW1,L,
     *    EEES1
 6001    FORMAT(//1X,*INPUT TAPE FORMAT*,//3X,*SCHOOL NUMBER =*,I3,2I2,3
     *    X,*ASPECT =*,F5.1,3X,*BEARING =*,F5.1,/5X,*DS =*,F7.1,3X,*DT =*
     *    ,F5.1,3X,*R =*,F7.1,3X,*MSE =*,F7.3,//3X,*SAMPLE PROCESSING *
     *    *NUMBER =*,4I2,3X,*D SNR =*,F6.1,3X,*BW =*,F7.1,/5X,*L =*,I3,3X
     *    ,*EEES =*,F7.3)
      IF(NF1(1).EQ.NF(1)) GOTO 18
        READ(1)
        IF(EOF(1).NE.0.) GOTO 999
        READ(1)
        IF(EOF(1).NE.0.) GOTO 999
        READ(1)
        IF(EOF(1).NE.0.) GOTO 999
        READ(1)
        IF(EOF(1).NE.0.) GOTO 999
        GOTO 16
C
C ***FISH SCHOOL SECTION***
C
   18 D=DS-DT $ D1=DS1-DT1
      SH=.057 $ SV=.086 $ SHP=5.7 $ SVP=8.6
      GH=SH*TWOPI*FO/CW $ GV=SV*TWOPI*FO/CW
      WRITE(6,6002)
 6002    FORMAT(//1X,*RUN PROGRESSION*,//2X,*FISH COODINATES AND *
     *    *CHARACTERISTICS SECTION*)
C   IF THE ORIENTATION IS THE SAME, GOTO 70
      IF(THD1.EQ.THD.A.BEAR1.EQ.BEAR.A.D1.EQ.D.A.R1.EQ.R) GOTO 70
      NW=1
      THL=(THD-THD1)/RADEG $ RMSEL=RMSE
      THS=SIN(THD/RADEG) $ THC=COS(THD/RADEG)
C   SCHOOL DIMENSIONS FROM ELLIPSOID
      THVE=RADEG*ATAN2(D,R)
      X1=R*THC $ Y1=-R*THS
      A2=A**2 $ B2=B**2
      DHE=R*ANGLE(X1,Y1)
      X1=-X1*100. $ Y1=Y1*100.
      DRE=R*100.*ANGLE(Y1,X1)
      DVE=2.*C
```

```
      BR=BEAR/RADEG
      SHS=SH/2.*SIN(BR) $ SHC=SH/2.*COS(BR)
C     IF NO CHANGE IN THE ASPECT ANGLE, GOTO 20
      IF(THL.EQ.0.) GOTO 20
        THLS=SIN(THL) $ THLC=COS(THL)
        WRITE(6,6005)
 6005       FORMAT(/3X,*NEW ORIENTATION: NEW COORDINATES,DELAYS, BEAM *
     *      *CORRECTIONS, AND MULTIPLE SCATTERING LOSSES*)
        READ(1)
        IF(EOF(1).NE.0.) GOTO 999
        READ(1) X,Y,Z,T,BCL,BCU,RMS,AMP,EFL,EFU,DP
        IF(EOF(1).NE.0.) GOTO 999
        DO 19 I=1,N
          XL=X(I)
          X(I)=XL*THLC-Y(I)*THLS
   19   Y(I)=XL*THLS+Y(I)*THLC
        GOTO 25
   20 WRITE(6,6010)
 6010     FORMAT(/3X,*NEW ORIENTATION: NEW DELAYS, BEAM CORRECTIONS, AND*
     *    * MULTIPLE SCATTERING LOSSES*)
      READ(1)
      IF(EOF(1).NE.0.) GOTO 999
      READ(1) X,Y,Z,T,BCL,BCU,RMS,AMP,EFL,EFU,DP
      IF(EOF(1).NE.0.) GOTO 999
   25 DO 60 I=1,N
        XR=R-X(I)
        ZD=(Z(I)+D)**2
        XYZ=SQRT(XR**2+Y(I)**2+ZD)
C
C *PROPAGATION DELAYS*
C
        T(I,1)=(SQRT((XR-SHS)**2+(Y(I)+SHC)**2+ZD)+XYZ)/CW
        T(I,2)=(SQRT((XR+SHS)**2+(Y(I)-SHC)**2+ZD)+XYZ)/CW
        T(I,3)=(SQRT(XR**2+Y(I)**2+(Z(I)+D-SV/2.)**2)+XYZ)/CW
        T(I,4)=(SQRT(XR**2+Y(I)**2+(Z(I)+D+SV/2.)**2)+XYZ)/CW
C
C *CALCULATION OF BEAM CORRECTIONS*
C
C       IF ANY FISH IS IN A SIDE LOBE, A NEW VARIABLE IS NEEDED
C       TO CHANGE THE SIGN OF AMP(I) FOR L-R,U-D.
        THH=(BR-ATAN2(Y(I),XR))**2
        THV=(ATAN2(Z(I)+D,SQRT(XR**2+Y(I)**2)))**2
        THVEQS=SQRT(THH*.4386+THV)*10.80713
        THHEQS=SQRT(THH+THV*2.28)*7.162545
        THVEQ=SQRT(THH*.110+THV)*10.80713
        THHEQ=SQRT(THH+THV*.549)*7.162545
        IF(THVEQS.LT..00001.O.THVEQ.LT..00001) GOTO 30
          E1=.017189*THVEQS+.2
          E2=.017189*THVEQ+.2
          BCL(I)=((ABS(SIN(THVEQS)/THVEQS))**E1+
          BCL(I)=((ABS(SIN(THVEQS)/THVEQS))**E1+
     *    (ABS(SIN(THVEQ)/THVEQ))**E2-2.)*45.
          GOTO 35
   30   BCL(I)=0.
   35   IF(THHEQS.LT..00001.O.THHEQ.LT..00001) GOTO 40
          E1=.017189*THHEQS+.2
          E2=.017189*THHEQ+.2
          BCU(I)=((ABS(SIN(THHEQS)/THHEQS))**E1+
     *    (ABS(SIN(THHEQ)/THHEQ))**E2-2.)*45.
          GOTO 45
   40   BCU(I)=0.
   45   CONTINUE
C       IF FIRST ORDER MULTIPLE SCATTERING IS USED,
C       THE NEXT LINE IS CHANGED.
```

```
          RMS(I)=RMSEL
   60 CONTINUE
      CALL STAT(X,N,XM,SX)
      CALL STAT(Y,N,YM,SY)
      CALL STAT(Z,N,ZM,SZ)
      CALL STAT(BCL,N,BCLM,SBCL)
      CALL STAT(BCU,N,BCUM,SBCU)
      CALL STAT(RMS,N,RMSM,SRMS)
C     SCHOOL DIMENSIONS FROM COORDINATES
      XR=R-XM
      THHC=BEAR-RADEG*ATAN2(YM,XR)
      ZD=D+ZM
      XYZ=SQRT(XR**2+YM**2)
      THVC=RADEG*ATAN2(ZD,XYZ)
      DHC=SR5*SY
      DVC=SR5*SZ
      DRC=SR5*SX
      GOTO 80
C
C
C     NO CHANGES IN ORIETATION
   70 RMSEL=RMSE/RMSE1
      WRITE(6,6015)
 6015     FORMAT(/3X,*SAME ORIENTATION*)
      READ(1) THVE,DHE,DVE,DRE,THVC,THHC,DHC,DVC,DRC,XM,SX,YM,SY,ZM,SZ,
     *    AMPM,SAMP,BCLM,SBCL,BCUM,SBCU,RMSM,SRMS,EFLM,SEFL,EFUM,SEFU,
     *    DPM,SDP
      IF(EOF(1).NE.0.) GOTO 999
      READ(1) X,Y,Z,T,BCL,BCU,RMS,AMP,EFL,EFU,DP
      IF(EOF(1).NE.0.) GOTO 999
      DO 75 I=1,N
          RMS(I)=RMS(I)*RMSEL
   75 CONTINUE
C     IF NO CHANGE IN AMPLITUDES, GOTO 100
   80 IF(NF1(2).EQ.NF(2)) GOTO 100
C
C *SCATTERING AMPLITUDE CALCULATIONS*
C
      NW=1
      WRITE(6,6025)
 6025     FORMAT(/3X,*NEW AMPLITUDES*)
C     IF EQUAL AMPLITUDES ARE DESIRED, GOTO 100
      IF(NF(2).EQ.0) GOTO 90
C     USE SEED ON FIRST SCHOOL ONLY
      IF(IR.GT.1) GOTO 82
        NR=NF(2)
        CALL RANSET(NSEED(NR))
   82 DO 85 I=1,N
          FM=RANF(0.)+.5
          RN=RANF(0.)
          RN=AMAX1(RN,.00001)
          AMP(I)=SQRT(-ALOG(RN)*(2.*FM**2))
   85 CONTINUE
      GOTO 96
C EQUAL AMPLITUDES FOR ALL FISH
   90 DO 95 I=1,N
          AMP(I)=1.0
   95 CONTINUE
   96 CALL STAT(AMP,N,AMPM,SAMP)
      GOTO 105
  100 WRITE(6,6030)
 6030     FORMAT(/3X,*SAME AMPLITUDES*)
C     IF NO CHANGE IN DOPPLER SHIFTS, GOTO 125
  105 IF(NF1(3).EQ.NF(3)) GOTO 125
```

```
C
C *DOPPLER CALCULATIONS*
C
      WRITE(6,6035)
 6035    FORMAT(/3X,*NEW DOPPLER DATA*)
C     IF NO DOPPLER SHIFTS DESIRED, GOTO 115
      IF(NF(3).EQ.0) GOTO 115
      IF(IR.GT.1) GOTO 107
      NR=NF(3)
      CALL RANSET(NSEED(NR))
  107 DO 110 I=1,N
         DP(I)=(RANF(0.)+.25)*F0/375.
  110 CONTINUE
      GOTO 121
C     NO DOPPLER SHIFTS USED
  115 DO 120 I=1,N
         DP(I)=0.
  120 CONTINUE
  121 CALL STAT(DP,N,DPM,SDP)
      GOTO 130
  125 WRITE(6,6040)
 6040    FORMAT(/3X,*SAME DOPPLER DATA*)
C     IF NO CHANGE IN ECHO ENERGIES, GOTO 140
  130 IF(NW.EQ.0) GOTO 140
C     TOTAL L-R AND U-D RECIEVED ENERGIES (CORRECTED AMPLITUDES SQUARED)
C     FOR EACH FISH
      DO 135 I=1,N
         XYZ=AMP(I)*RMS(I)
         E=BCL(I)/20.
         EFL(I)=(XYZ*10.**E)**2
         E=BCU(I)/20.
         EFU(I)=(XYZ*10.**E)**2
  135 CONTINUE
      CALL STAT(EFL,N,EFLM,SEFL)
      CALL STAT(EFU,N,EFUM,SEFU)
  140 CONTINUE
C
C ***ECHO PROCESSING SECTION***
C
      WRITE(6,6045)
 6045    FORMAT(//2X,*QUAD SAMPLE, FILTER, AND NOISE SECTON*)
C     IF THE SAME SAMPLES ARE USED, GOTO 200
      IF(NS1(1).EQ.NS(1)) GOTO 200
      WRITE(6,6050)
 6050    FORMAT(/3X,*NEW UNFILTERED QUAD SAMPLES*)
C     CALCULATE THE NUMBER OF SAMPLES IN UNFILTERED ECHO
      VMX=AMAX1(T(1,1),T(1,2),T(1,3),T(1,4))
      VMN=AMIN1(T(1,1),T(1,2),T(1,3),T(1,4))
      DO 145 I=2,N
         VMX1=AMAX1(T(I,1),T(I,2),T(I,3),T(I,4))
         VMN1=AMIN1(T(I,1),T(I,2),T(I,3),T(I,4))
         VMX=AMAX1(VMX1,VMX)
         VMN=AMIN1(VMN1,VMN)
  145 CONTINUE
      VMX=VMX+PW
      LMX=INT(FS*VMX)
      LMN=INT(FS*VMN)+1
      L=LMX-LMN+1
      IF(L.GT.100) GOTO 999
      RLT=LMN/FS
      RLT1=RLT
C     CALCULATE EXPECTED UNFILTERED SIGNAL AND NOISE ENERGIES
      X1=N*AINT(PW*FS+.000001)*.375
      EESL=EFLM*X1
```

```
      EESU=EFUM*X1
      EEN=2.*L
      EES=EEES
C     IF NO EXTERNAL EXPECTED ENERGY (EEES) IS SPECIFIED,
C     THEN USE THE MEAN OF THE L-R AND U-D EXPECTED ENERGIES.
      IF(EEES.EQ.0.) EES=(EESL+EESU)/2.
      CALL NGAIN(EES,EEN,DSNR,G)
C
C *LOOP TO GENERATE UNFILTERED QUAD SAMPLES*
C
C     GENERATE SIGNAL COMPONENTS
      FSL=1./FS
      DO 147 I=  4
  147 ES(I)=EN(I)=0.
      EAL=EAU=DAL=DAU=0.
      DO 167 I=1,L
         DO 150 J=1,4
  150    QS(I,J,1)=QS(I,J,2)=0.
         SF(I)=X1=Y1=0.
         DO 160 J=1,N
            XR=SQRT(EFL(J))
            XYZ=SQRT(EFU(J))
            DO 155 K=1,4
               PU=PULSE(RLT-T(J,K),J)
               IF(PU.EQ.0.) GOTO 155
                 YR=TWOPI*(F0+DP(J))*T(J,K)
                 IF(K.GT.2) XR=XYZ
                 QS(I,K,1)=QS(I,K,1)+XR*PU*COS(YR)
                 QS(I,K,2)=QS(I,K,2)+XR*PU*SIN(YR)
  155       CONTINUE
            IF(PU.EQ.0.) GOTO 160
            SF(I)=SF(I)+1.
            X1=X1+EFL(J)
            Y1=Y1+EFU(J)
  160    CONTINUE
         DO 165 J=1,4
            ESS(I,J)=QS(I,J,1)**2+QS(I,J,2)**2
  165    ES(J)=ES(J)+ESS(I,J)
         RLT=RLT+FSL
         EAL=EAL+X1
         EAU=EAU+Y1
         DAL=DAL+X1**2
         DAU=DAU+Y1**2
         SDA(I,1)=X1
  167 SDA(I,2)=Y1
C     GENERATE NOISE COMPONENTS
      IF(IR.GT.1) GOTO 168
        NR=NS(4)
        CALL RANSET(NSEED(NR))
  168 DO 175 I=1,L
         DO 170 J=1,4
            RN=RANF(0.)
            RN=AMAX1(RN,.00001)
            X1=SQRT(-2.*ALOG(RN))
            Y1=TWOPI*RANF(0.)
            QN(I,J,1)=X1*COS(Y1)*G
            QN(I,J,2)=X1*SIN(Y1)*G
            X1=QN(I,J,1)**2+QN(I,J,2)**2
            ESS(I,J)=AMAX1(ESS(I,J),.000001)
            SSNR(I,J)=10.*ALOG10(ESS(I,J)/X1)
  170    EN(J)=EN(J)+X1
  175 CONTINUE
      RLTE=RLT-FSL
C IF FILTER IS DESIRED, GOTO 180
```

```
      IF(NS(2).NE.0) GOTO 180
        WRITE(6,6055)
 6055       FORMAT(/3X,*NO FILTER APPLIED*)
        IF(NF1(2).EQ.-1) GOTO 350
        READ(1)
        IF(EOF(1).NE.0.) GOTO 999
        READ(1)
        IF(EOF(1).NE.0.) 999,350
C
C *SAMPLE FILTERING*
C
  180 NS1(2)=0
      READ(1)
      IF(EOF(1).NE.0.) 999,201
C    SAME CARRIER FREQUENCY, SAMPLE FREQUENCY,AND PULSE WIDTH
C    SO GET ENERGIES FROM TAPE1.
  200 READ(1) ES,EESL,EESU,EN,EEN,EAL,EAU,DAL,DAU
      IF(EOF(1).NE.0.) GOTO 999
C    IF SAME FILTERED ENERGIES ARE TO BE USED, GOTO 300.
      IF(NS1(2).EQ.NS(2)) GOTO 300
      WRITE(6,6060)
 6060     FORMAT(/3X,*APPLY NEW FILTER TO SAME SAMPLES*)
C    TAPE1 SAMPLES MUST BE UNFILTERED HERE.
      IF(NS1(2).NE.0) GOTO 999
      GOTO 202
  201 WRITE(6,6065)
 6065     FORMAT(/3X,*APPLY NEW FILTER TO NEW SAMPLES*)
C   CALCULATE EXPECTED FILTERED SIGNAL AND NOISE ENERGIES
C    CALCULATE "A" GIVEN BW AND 50 DIVISIONS IN HANNING PULSE.
  202 XR=2.*COS(TWOPI*BW*PW/50.)-4.
      AF=(-XR-SQRT(XR**2-4.))/2.
      XYZ=1.-AF
C    LOOP TO CALCULATE EXPECTED FILTERED XMT PULSE ENERGY
      EPF=X1=0.
      DO 205 I=1,50
         X1=AF*X1+XYZ*(SIN(PI*I/50.)**2)
         EPF=EPF+X1**2
  205 CONTINUE
      I=50
  210 I=I+1
      IF(I.GT.500) GOTO 999
      X1=X1*AF
      WT=X1**2
      EPF=EPF+WT
      IF(WT.GE..01*EPF) GOTO 210
      Y2=EPF/50./.375
      EESL=EESL*Y2
      EESU=EESU*Y2
      EES=EEES
      IF(EEES.EQ.0.) EES=(EESL+EESU)/2.
C   APPLY FILTER TO SIGNAL AND NOISE SAMPLES
C    CALCULATE "A" GIVEN BW AND FS
      XR=2.*COS(TWOPI*BW/FS)-4.
      AF=(-XR-SQRT(XR**2-4.))/2.
      XYZ=1.-AF
      OUF=SQRT(EEN/2./L)
      AFR=XYZ/(1.+AF)
      ASR=SQRT(AFR)
      EEN=EEN*AFR
      CALL NGAIN(EES,EEN,DSNR,G)
C    IF TAPE1 SAMPLES CAN'T BE USED, GOTO 214
      IF(NS1(1).NE.NS(1)) GOTO 214
      READ(1) QS,QN,SF,SDA
      IF(EOF(1).NE.0.) GOTO 999
```

```
C    USE RANF SEED ON FIRST SCHOOL ONLY.
 214 IF(IR.GT.1) GOTO 215
     NR=NS(4)
     CALL RANSET(NSEED(NR))
CALCULATE Y(-1) PRE-ECHO NOISE FILTER TERMS
 215 DO 220 J=1,4
        RN=RANF(0.)
        RN=AMAX1(RN,.00001)
        X1=SQRT(-2.*ALOG(RN))
        Y1=TWOPI*RANF(0.)
        QS(1,J,1)=QS(1,J,1)*XYZ $ QS(1,J,2)=QS(1,J,2)*XYZ
        QN(1,J,1)=X1*COS(Y1)*GUF*G*AFSR*AF+QN(1,J,1)*XYZ*G
        QN(1,J,2)=X1*SIN(Y1)*GUF*G*AFSR*AF+QN(1,J,2)*XYZ*G
        ES(J)=QS(1,J,1)**2+QS(1,J,2)**2
        ESS(I,J)=ES(J)
        EN(J)=QN(1,J,1)**2+QN(1,J,2)**2
        ES(J)=AMAX1(ES(J),.000001)
 220 SSNR(1,J)=10.*ALOG10(ES(J)/EN(J))
     DO 235 I=2,L
        DO 230 J=1,4
        X1=Y1=0.
        DO 225 K=1,2
           QS(I,J,K)=QS(I-1,J,K)*AF+QS(I,J,K)*XYZ
           QN(I,J,K)=QN(I-1,J,K)*AF+QN(I,J,K)*XYZ*G
           X1=X1+QS(I,J,K)**2
 225    Y1=Y1+QN(I,J,K)**2
        ESS(I,J)=X1
        ES(J)=ES(J)+X1
        EN(J)=EN(J)+Y1
        X1=AMAX1(X1,.000001)
 230    SSNR(I,J)=10.*ALOG10(X1/Y1)
 235 CONTINUE
C    LOOP TO SAMPLE FILTER TAIL
     I=L
 240 I=I+1
     IF(I.GT.100) GOTO 999
     SSNRP=0.
C GENERATE MORE NOISE SAMPLES
     DO 250 J=1,4
        RN=RANF(0.)
        RN=AMAX1(RN,.00001)
        X1=SQRT(-2.*ALOG(RN))
        X1=SQRT(-2.*ALOG(RN))
        Y1=TWOPI*RANF(0.)
        QN(I,J,1)=X1*COS(Y1)
        QN(I,J,2)=X1*SIN(Y1)
        X1=Y1=0.
        DO 245 K=1,2
           QS(I,J,K)=QS(I-1,J,K)*AF
           QN(I,J,K)=QN(I-1,J,K)*AF+QN(I,J,K)*XYZ*G*GUF
           X1=X1+QN(I,J,K)**2
 245    Y1=Y1+QS(I,J,K)**2
        X1=AMAX1(X1,.0000001)
        Y1=AMAX1(Y1,.000001)
        SSNR(I,J)=10.*ALOG10(Y1/X1)
 250 SSNRP=SSNRP+SSNR(I,J)
C IF THE AVERAGE SAMPLE SNR IS LESS THAN DSNR/10, GOTO 260.
     IF(SSNRP.LT.DSNR/2.5) GOTO 260
     DO 255 J=1,4
        ESS(I,J)=Y1
        EN(J)=EN(J)+X1
 255 ES(J)=ES(J)+Y1
     SF(I)=SDA(I,1)=SDA(I,2)=0.
     RLTE=RLTE+1./FS
```

```
      GOTO 240
  260 L=I-1
      GOTO 350
C     CHANGE S/N RATIO ONLY
  300 WRITE(6,6070)
 6070    FORMAT(/3X,*SAME SAMPLES WITH NEW S/N RATIO*)
      READ(1) QS,QN,SF,SDA,SSNR
      IF(EOF(1).NE.0.) GOTO 999
      EES=EEES
      IF(EEES.EQ.0.) EES=(EESL+EESU)/2.
C     IF DSNR ON TAPE1 IS OK, GOTO 350.
      IF(DSNR1.EQ.DSNR) GOTO 350
  301 CALL NGAIN(EES,EEN,DSNR,G)
      IF(NS(2).NE.0) GOTO 999
      X1=-10.*ALOG10(G**2)
      DO 310 I=1,L
         DO 305 J=1,4
            QN(I,J,1)=QN(I,J,1)*G
            QN(I,J,2)=QN(I,J,2)*G
  305    SSNR(I,J)=SSNR(I,J)+X1
  310 CONTINUE
      DO 315 J=1,4
  315 EN(J)=EN(J)*G**2
C COMBINED SIGNAL PLUS NOISE SAMPLES AND SCHOOL CHARACTERISTICS
  350 QLR=QLI=QUR=QUI=0.
      DO 351 I=1,4
         EQ(I)=DQ(I)=0.
  351 CONTINUE
      IF(NS(3).EQ.0) GOTO 355
      WRITE(6,6075)
 6075    FORMAT(/3X,*RESULTS CALCULATED FROM SIGNAL PLUS NOISE*)
      DO 354 I=1,L
         DO 353 J=1,4
         X1=0.
         DO 352 K=1,2
            Q(I,J,K)=QS(I,J,K)+QN(I,J,K)
  352    X1=X1+Q(I,J,K)**2
         SDQ(I,J)=X1
         EQ(J)=EQ(J)+X1
         DQ(J)=DQ(J)+X1**2
  353    CONTINUE
  354 CONTINUE
      GOTO 358
  355 WRITE(6,6080)
 6080    FORMAT(/3X,*RESULTS CALCULATED FROM SIGNAL WITHOUT NOISE*)
      DO 357 J=1,4
         EQ(J)=ES(J)
         DO 356 I=1,L
            Q(I,J,1)=QS(I,J,1) $ Q(I,J,2)=QS(I,J,2)
            SDQ(I,J)=ESS(I,J)
  356    DQ(J)=DQ(J)+ESS(I,J)**2
  357 CONTINUE
C
C *L-R AND U-D SAMPLE CROSSCORRELATIONS*
C
  358 DO 365 I=1,L
         QLR=QLR+Q(I,1,1)*Q(I,2,1)+Q(I,1,2)*Q(I,2,2)
         QLI=QLI+Q(I,1,2)*Q(I,2,1)-Q(I,1,1)*Q(I,2,2)
         QUR=QUR+Q(I,3,1)*Q(I,4,1)+Q(I,3,2)*Q(I,4,2)
  365 QUI=QUI+Q(I,3,2)*Q(I,4,1)-Q(I,3,1)*Q(I,4,2)
C     NORMALIZATION
      DALN=EAL**2/DAL
      DAUN=EAU**2/DAU
      CAL=SQRT(QLR**2+QLI**2)
```

```
      CAU=SQRT(QUR**2+QUI**2)
      CALN=CAL/SQRT(EQ(1)*EQ(2))
      CAUN=CAU/SQRT(EQ(3)*EQ(4))
      DO 390 J=1,4
         ES(J)=AMAX1(ES(J),.000001)
         ASNR(J)=10.*ALOG10(ES(J)/EN(J))
         DQ(J)=EQ(J)**2/DQ(J)
         ENN(J)=EN(J)/EEN
         ESN(J)=ES(J)/EES
         EQN(J)=EQ(J)/(EES+EEN)
         IF(NS(3).EQ.0) EQN(J)=ESN(J)
C     NORMALIZED QUAD SAMPLES
  380    X2(J)=SQRT(EQ(J))
         DO 385 I=1,L
            SDQ(I,J)=SDQ(I,J)/EQ(J)
            Q(I,J,1)=Q(I,J,1)/X2(J)
  385    Q(I,J,2)=Q(I,J,2)/X2(J)
  390 CONTINUE
      EEQ=EES+EEN
      IF(NS(3).EQ.0) EEQ=EES
      DO 391 I=1,L
         SDAN(I,1)=SDA(I,1)/EAL
  391 SDAN(I,2)=SDA(I,2)/EAU
C
C *SCHOOL LOCATIONS AND DIMENSIONS FROM QUAD SAMPLES*
C
      THHQ=-ATAN2(QLI,QLR)*RADEG/GH
      THVQ=-ATAN2(QUI,QUR)*RADEG/GV
      IF(CALN.LE.1.) GOTO 395
      CALP=1.
      GOTO 400
  395 CALP=CALN
  400 IF(CAUN.LE.1.) GOTO 405
      CAUP=1.
      GOTO 410
  405 CAUP=CAUN
  410 X1=SR2/GH*SQRT(1.-CALP)
      Y1=SR2/GV*SQRT(1.-CAUP)
      DHQ(1)=SR5*R*X1
      DVQ(1)=SR5*R*Y1
      DHQ(2)=X1*RADEG
      DVQ(2)=Y1*RADEG
      X1=1800./FS
      DRQ(1)=(DQ(1)+DQ(2)+DQ(3)+DQ(4))/4.*X1
      DRQ(2)=(DALN+DAUN)/2.*X1
C
C ***DATA STORAGE ON TAPE SECTION***
C
      WRITE(2) NF,THD,BEAR,DS,DT,R,RMSE,NS,ASNR,DSNR,BW,L,EEES,
     *   VMN,RLTE,RLT1,VMX
      WRITE(2) THVE,DHE,DVE,DRE,THVC,THHC,DHC,DVC,DRC,XM,SX,YM,SY,ZM,SZ,
     *   AMPM,SAMP,BCLM,SBCL,BCUM,SBCU,RMSM,SRMS,EFLM,SEFL,EFUM,SEFU,
     *   DPM,SDP
      WRITE(2) X,Y,Z,T,BCL,BCU,RMS,AMP,EFL,EFU,DP
      WRITE(2) ES,EESL,EESU,EN,EEN,EAL,EAU,DAL,DAU
      WRITE(2) QS,QN,SF,SDAN,SSNR,SDQ
      WRITE(4) NF,NS,RMSE,THHC,THVC,DHC,DVC,DRC,THHQ,THVQ,DHQ(1),DVQ(1),
     *   DRQ,EQN,CAL,CAU,CALN,CAUN
      WRITE(6,6085)
 6085    FORMAT(//1X,*DATA WRITTEN ON DISK*)
C
C ***PRINT SECTION***
C
C  *FISH LOCATIONS, DELAY TIMES AND CHARACTERISTICS*
```

```
      IF(NP(1).EQ.0.O.ISNR.GT.0) GOTO 510
      WRITE(6,6100) (NF(I),I=1,3)
 6100    FORMAT(1H1,1X,*FISH LOCATIONS, DELAY TIMES, AND CHARACTERISTICS
     *   *,//3X,*SCHOOL NUMBER =*,I3,10X,*AMPLITUDE SEED =*,I2,10X,*DOPP
     *   LER SEED =*,I2,//3X,*NO.*,3X,*X (M)*,4X,*Y*,7X,*Z*,6X,*TL (SEC)
     *   *,4X,*TR*,8X,*TU*,8X,*TD*,7X,*AMPL*,8X,*BEAM*,7X,*MULT*,8X,*TOT
     *   AL*,7X,*DOPP*,/86X,*CORR*,7X,*SCAT*,8X,*ENERGY*,/)
      DO 500 I=1,N
         WRITE(6,6105) I,X(I),Y(I),Z(I),(T(I,J),J=1,4),AMP(I),BCL(I),
     *      BCU(I),RMS(I),EFL(I),EFU(I),DP(I)
 6105       FORMAT(1X,I4,3F8.2,1X,4F10.7,F8.2,2(2X,2F6.1,F9.2))
  500 CONTINUE
      WRITE(6,6110) XM,YM,ZM,AMPM,BCLM,BCUM,RMSM,EFLM,EFUM,DPM,SX,SY,SZ,
     *   SAMP,SBCL,SBCU,SRMS,SEFL,SEFU,SDP
 6110    FORMAT(/1X,*MEAN*,41X,F8.2,2(2X,2F6.1,F9.2),/2X,*SD *,3F8.2,
     *   3F8.2,41X,F8.2,2(2X,2F6.1,F9.2))
C
C *NORMALIZED SIGNAL (OR SIGNAL PLUS NOISE) SAMPLES AND CHARACTERISTICS*
C
  510 IF(NP(2).EQ.0) GOTO 545
      WRITE(6,6115) VMN,RLTE,RLT1,VMX
 6115    FORMAT(1H1,1X,*NORMALIZED QUADRATURE SAMPLES AND SAMPLE *
     *   *CHARACTERISTICS*,//3X,*TIME OF FIRST RETURN =*,F7.4,10X,
     *   *TIME OF LAST SAMPLE =*,F7.4,/3X,*TIME OF FIRST SAMPLE =*,
     *   F7.4,10X,*END OF LAST RETURN  =*,F7.4)
      IF(NS(2).EQ.0) GOTO 515
      WRITE(6,6120) BW
 6120    FORMAT(/3X,*FILTER BANDWIDTH =*,F6.1,2X,*HZ*)
  515 IF(NS(3).EQ.0) GOTO 530
C     SIGNAL PLUS NOISE QUAD SAMPLES
      WRITE(6,6125) NS(4)
 6125    FORMAT(/3X,*SAMPLES OF SIGNAL PLUS NOISE*,10X,*NOISE SEED =*,I2
     *   ,//3X,*NO.*,7X,*LEFT*,12X,*RIGHT*,11X,*UP*,14X,*DOWN*,10X,*SNR*
     *   ,4X,*FISH/*,10X,*DENSITIES*,/82X,*SAMPLE*,3X,*FISH AMPL*,3X,
     *   *QUAD SAMPLES*,/)
      DO 525 I=1,L
         SSNRP=SDQP=0.
         DO 520 J=1,4
            SSNRP=SSNRP+SSNR(I,J)
  520    SDQP=SDQP+SDQ(I,J)
         SSNRP=SSNRP/4.
         SDQP=SDQP/4.
         SDAP=(SDAN(I,1)+SDAN(I,2))/2.
         WRITE(6,6130) I,((Q(I,J,K),K=1,2),J=1,4),SSNRP,SF(I),SDAP,SDQP
 6130    FORMAT(1X,I4,4(2X,2F7.4),4X,F6.1,3X,F4.0,2F12.3)
  525 CONTINUE
      GOTO 545
C     SNR=INFINITY
  530 WRITE(6,6135)
 6135    FORMAT(/3X,*SAMPLES OF SIGNAL ONLY*,//3X,*NO.*,7X,*LEFT*,12X,
     *   *RIGHT*,11X,*UP*,14X,*DOWN*,7X,*FISH/*,10X,*DENSITIES*,/72X,
     *   *SAMPLE*,3X,*FISH AMPL*,3X,*QUAD SAMPLES*,/)
      DO 540 I=1,L
         SDQP=0.
         DO 535 J=1,4
  535    SDQP=SDQP+SDQ(I,J)/4.
         SDAP=(SDAN(I,1)+SDAN(I,2))/2.
         WRITE(6,6140) I,((Q(I,J,K),K=1,2),J=1,4),SF(I),SDAP,SDQP
 6140    FORMAT(1X,I4,4(2X,2F7.4),3X,F4.0,2F12.3)
  540 CONTINUE
C
C *UNNORMALIZED SIGNAL AND NOISE COMPONENTS OF QUAD SAMPLES*
C
  545 IF(NP(3).EQ.0) GOTO 555
```

```
      WRITE(6,6145) NS(4),DSNR
 6145    FORMAT(1H1.1X,*UNNORMALIZED SIGNAL AND NOISE COMPONENTS OF *
     *   *QUADRATURE SAMPLES*,//3X,*NOISE SEED =*,I2,5X,
     *   *DESIRED S/N RATIO =*,F6.2)
      IF(NS(3).NE.0) GOTO 546
      WRITE(6,6146)
 6146    FORMAT(/3X,*NOISE NOT INCLUDED IN SAMPLE PROCESSING*)
  546 WRITE(6,6147)
 6147    FORMAT(/3X,*NO.*,13X,*LEFT*,27X,*RIGHT*,26X,
     *   *UP*,29X,*DOWN*,/11X,*SIGNAL*,9X,*NOISE*,11X,*SIGNAL*,9X,*NOISE
     *   *,11X,*SIGNAL*,9X,*NOISE*,11X,*SIGNAL*,9X,*NOISE*,/)
      DO 550 I=1,L
         WRITE(6,6150) I,(((QS(I,J,K),K=1,2),(QN(I,J,K),K=1,2)),J=1,4)
 6150       FORMAT(1X,I3,4(2X,F6.3,F7.3,1X,F7.4,F8.4))
  550 CONTINUE
C
C *INPUT DATA AND COMPUTED RESULTS*
C
  555 WRITE(6,6155) NF(1),N,SHP,NF(2),SVP,NF(3),FOP,R,PWP,DS,DT,BEAR,
     *   A,B,C,THD,FSP
 6155    FORMAT(1H1,1X,*INPUT DATA AND COMPUTED RESULTS*,//3X,
     *   *INPUT DATA*,//4X,*SCHOOL CHARACTERISTICS*,30X,*TRANSDUCER *
     *   *CHARACTERISTICS*,//5X,*SCHOOL NO. =*,12X,I3,/5X,
     *   *NO. OF FISH =*,10X,I4,25X,
     *   *HORIZONTAL SEPARATION =*,5X,F4.1,*   CM*,/7X,*AMPLITUDE SEED =
     *   *,7X,I2,25X,*VERTICAL SEPARATION =*,7X,F4.1,*   CM*,/7X,
     *   *DOPPLER SEED =*,9X,I2,25X,*FREQUENCY =*,15X,F8.3,* KHZ*,
     *   /5X,*RANGE =*,15X,F7.1,*   M*,19X,*PULSE LENGTH =*,14X,F6.3,
     *   * MSEC*,
     *   /5X,*SCHOOL DEPTH =*,9X,F6.1,*   M*,19X,*TRANSDUCER DEPTH =*,8X
     *   ,F6.1,*   M*,
     *   /5X,*ELLIPSOID PARAMETERS*,32X,*BEARING TO SCHOOL (+=CCW) =*,
     *   F5.1,*   DEG*,
     *   /7X,13HA (*X*AXIS) =,9X,F5.1,*   M*,/7X,13HB (*Y*AXIS) =,9X,
     *   ,F5.1,*   M*,
     *   /7X,*C (Z AXIS) =*,10X,F5.1,*   M*,/7X,*ASPECT ANGLE (+=CCW) =*
     *   F5.1,*   DEG*,
     *   //4X,*SAMPLER CHARACTERISTICS*,//5X,*SAMPLE FREQUENCY =*,5X,
     *   F8.3,* KHZ*)
      IF(NS(2).EQ.0) GOTO 556
      WRITE(6,6156) BW
 6156    FORMAT(5X,*FILTER BANDWIDTH =*,5X,F6.1,*   HZ*)
      GOTO 557
  556 WRITE(6,6157)
 6157    FORMAT(5X,*NO FILTER*)
  557 IF(NS(3).EQ.0) GOTO 558
      WRITE(6,6158) DSNR,NS(4)
 6158    FORMAT(5X,*S/N RATIO =*,14X,F4.1,*   DB*,/5X,*NOISE SEED =*,
     *   11X,I4)
      GOTO 559
  558 WRITE(6,6159)
 6159    FORMAT(5X,*NO NOISE*)
C    COMPUTED SCHOOL CHARACTERISTICS
  559 WRITE(6,6160)
 6160    FORMAT(//1X,*COMPUTED SCHOOL CHARACTERISTICS AS SEEN FROM *
     *   *TRANSDUCER*,//3X,*EXPECTED AND ACTUAL COMPUTED VALUES*)
      IF(NS(3).EQ.0) GOTO 561
      WRITE(6,6165) (ESN(J),J=1,4),EES
 6165    FORMAT(/5X,*ENERGIES NORMALIZED TO THEIR EXPECTED VALUES*,
     *   //19X,*LEFT*,5X,*RIGHT*,6X,*UP*,8X,*DOWN*,7X,*EXPECTED*,
     *   //7X,*SIGNAL*,4F10.3,F13.3)
      IF(EEES.EQ.0.) GOTO 560
      WRITE(6,6166)
 6166   FORMAT(1H+,3X,*(EXPECTED ENERGY NOT CALCULATED FROM THIS PING)*)
```

```
 560 WRITE(6,6167) (ENN(J),J=1,4),EEN,(EQN(J),J=1,4),EEQ,
    *   (ASNR(J),J=1,4),DSNR
6167    FORMAT(7X,*NOISE *,4F10.3,F13.3,/7X,*ECHO*,2X,4F10.3,F13.3,
    *   //7X,*SNR*,3X,4F10.3,F13.3)
     GOTO 565
 561 WRITE(6,6170) (ESN(J),J=1,4),EES
6170    FORMAT(/5X,*SIGNAL ENERGIES NORMALIZED TO THEIR EXPECTED *,
    *   *VALUE*,//8X,*LEFT*,5X,*RIGHT*,6X,*UP*,8X,*DOWN*,7X,*EXPECTED*,
    *   //2X,4F10.3,F13.3)
     IF(EEES.EQ.0.) GOTO 565
     WRITE(6,6171)
6171   FORMAT(1H+,3X,*(EXPECTED ENERGY NOT CALCULATED FROM THIS PING)*)
C    CORRELATION AMPLITUDES
 565 WRITE(6,6175) CAL,CALN,CAU,CAUN
6175    FORMAT(/5X,*CORRELATION AMPLITUDES*,//26X,*UNNORM*,
    *   13X,*NORM*,//7X,*LEFT/RIGHT*,F15.3,F18.6,/7X,*UP/DOWN*,3X,F15.3
    *   ,F18.6)
C    SCHOOL CHARACTERISTICS
     WRITE(6,6180) BEAR,THHC,THHQ,THVE,THVC,THVQ,DHE,DHC,(DHQ(I),I=1,2)
    *   ,DVE,DVC,(DVQ(I),I=1,2),DRE,DRC,(DRQ(I),I=1,2)
6180    FORMAT(/3X,*SCHOOL CHARACTERISTICS*,//5X,*ANGLES TO SCHOOL*,
    *   /28X,*ELLIPSOID*,8X,*FISH LOCATIONS*,10X,*QUAD SAMPLES*,
    *   //7X,*HORIZONTAL*,3(F16.2,* DEG*),/7X,*VERTICAL  *,3(F16.2,
    *   * DEG*),/7X,
    *   /5X,*SCHOOL DIMENSIONS*,//7X,*HORIZONTAL*,2(F16.2,* M  *),
    *   4X,F8.2,* M  *,F8.2,* DEG*,
    *   /7X,*VERTICAL  *,2(F16.2,* M  *),4X,F8.2,* M  *,F8.2,
    *   * DEG*,/7X,
    *   *DOWN RANGE*,
    *   2(F16.2,* M  *),4X,2(F8.2,* M  *),1X,*(QUAD,AMP)*,//87X,
    *   16HDIM=2*SQRT(5)*SD)
C
C
C    IF ONLY ONE SNR IS DESIRED OF LAST SNR HAS BEEN
C    COMPUTED FOR THIS PING, GOTO 990
     IF(ISNRM.EQ.1.O.ISNR.EQ.ISNRM) GOTO 990
     NS(2)=0
     NS(3)=NS(3)+1
     ISNR=ISNR+1
     DSNR=DSN(ISNR)
     WRITE(6,6185)
6185    FORMAT(1H1,3X,*SAME SAMPLES WITH NEW S/N RATIO*)
     GOTO 301
 990 IR=IR+1
     IF(IR.GT.IRM) GOTO 999
     GOTO 10
 999 STOP
     END
C
C**************************************************************************
C
     FUNCTION PULSE (T,I)
C CALCULATES AMPLITUDE OF SIGNAL RETURN FROM FISH "I" AT TIME "T"
     COMMON /PLSE/PW,F0,DP(500)
     PW1=PW*F0/(F0+DP(I))
     IF(T.LT.0..OR.T.GT.PW1) 1,2
   1 PULSE=0.
     GOTO 3
   2 PULSE=(SIN(T*3.141592654/PW1))**2
   3 CONTINUE
     RETURN
     END
C
C
```

```
      FUNCTION ANGLE(X1,Y1)
C COMPUTES ANGLE BETWEEN TANGENTS TO ELLIPSE FROM TRANSDUCER
      COMMON /ANGL/A,A2,B2,PI
      SLP=SQRT(B2*X1**2+A2*Y1**2-A2*B2)
      PI1=0.
      SGN1=SGN2=1.
      IF(X1.LT.0.0) SGN1=-1.
      IF(SGN1*X1-A) 10,30,20
   10 PI1=PI
      SGN2=-1.0
   20 SLP1=(X1*Y1-SLP)/(X1**2-A2)
      SLP2=(X1*Y1+SLP)/(X1**2-A2)
      GOTO 40
   30 SLP1=(X1*Y1-SLP)/(Y1**2-B2)
      SLP2=(X1*Y1+SLP)/(Y1**2-B2)
   40 ANGLE=SGN2*ABS(ATAN(SLP1)-ATAN(SLP2))+PI1
      RETURN
      END
C
C
      SUBROUTINE STAT(SA,IS,SM,SSD)
C CALCULATES MEAN AND STANDARD DEVIATION OF A SEQUENCE
      DIMENSION SA(IS)
      SM=SSD=0.
      DO 10 I=1,IS
         SM=SM+SA(I)
   10 CONTINUE
      SM=SM/IS
      DO 20 I=1,IS
         SSD=SSD+(SA(I)-SM)**2
   20 CONTINUE
      SSD=SQRT(SSD/IS)
      RETURN
      END
C
C
      SUBROUTINE NGAIN(ES,EN,DSNR,G)
C NOISE GAIN TO ACHIEVE DESIRED S/N RATIO
      SNR=10.*ALOG10(ES/EN)
      E=(SNR-DSNR)/20.
      G=10.**E
      EN=EN*G**2
      RETURN
      END
```

-END OF INFORMATION-
?

APPENDIX E

FORMULATION OF AMPLITUDE CORRECTIONS FOR

TRANSDUCER BEAM PATTERNS

The echo amplitude of each fish is partially determined by its position in the beam pattern. This appendix shows how these amplitude corrections are derived from the calibration curves of an actual transducer used in a split-beam system. The transducer is composed of many elements which are grouped into four quadrants as shown in Fig. 13.

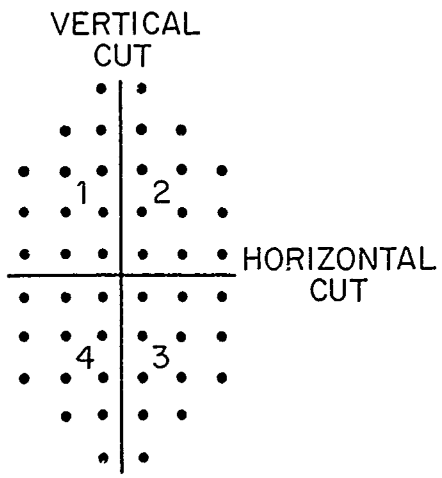


Figure 13. Diagram of actual split-beam transducer.

Quadrants 1 and 2 are summed and quadrants 3 and 4 are summed to obtain the up-down transducer-half signals, while 1 and 4 along with 2 and 3 provide the left-right signals. The transmit pulse originates from all quadrants simultaneously.

Horizontal (90° cut) and vertical (0° cut) calibration data for the different configurations are shown in Fig. 14. The isolated points on the calibration curves are the values of Eq. 22, which was chosen to fit the curves and used in the simulation.

$$\left|\frac{\sin\phi}{\phi}\right|^{(0.017189\,\phi + 0.2)} , \tag{22}$$

where

$$\phi = \begin{cases} \dfrac{\pi\,\theta}{16.66} & \text{XMT and left-right } 0^\circ \text{ cut} \\[2ex] \dfrac{\pi\,\theta}{25.13} & \text{XMT and up-down } 90^\circ \text{ cut} \end{cases}$$

(Note: θ is in degrees; ϕ is in radians.)

The two-dimensional angular position of each fish can be transformed into a one-dimensional angle which has the same beam strength on the calibration curve. To accomplish this transformation, the beam patterns are assumed to be elliptical with constant eccentricities. The eccentricities, computed as the ratio of the horizontal (90° cut) to vertical (0° cut) main lobe widths, are 1.51, 3.02, and 0.741, for the transmit, left-right, and up-down beams. These are the values of ε in Eq. 7 which are used to obtain the equivalent one-dimensional angles. Amplitude corrections are computed from the equivalent angles for combinations of the transmit and left-right beams or the transmit and up-down beams as described in Chapter 3.

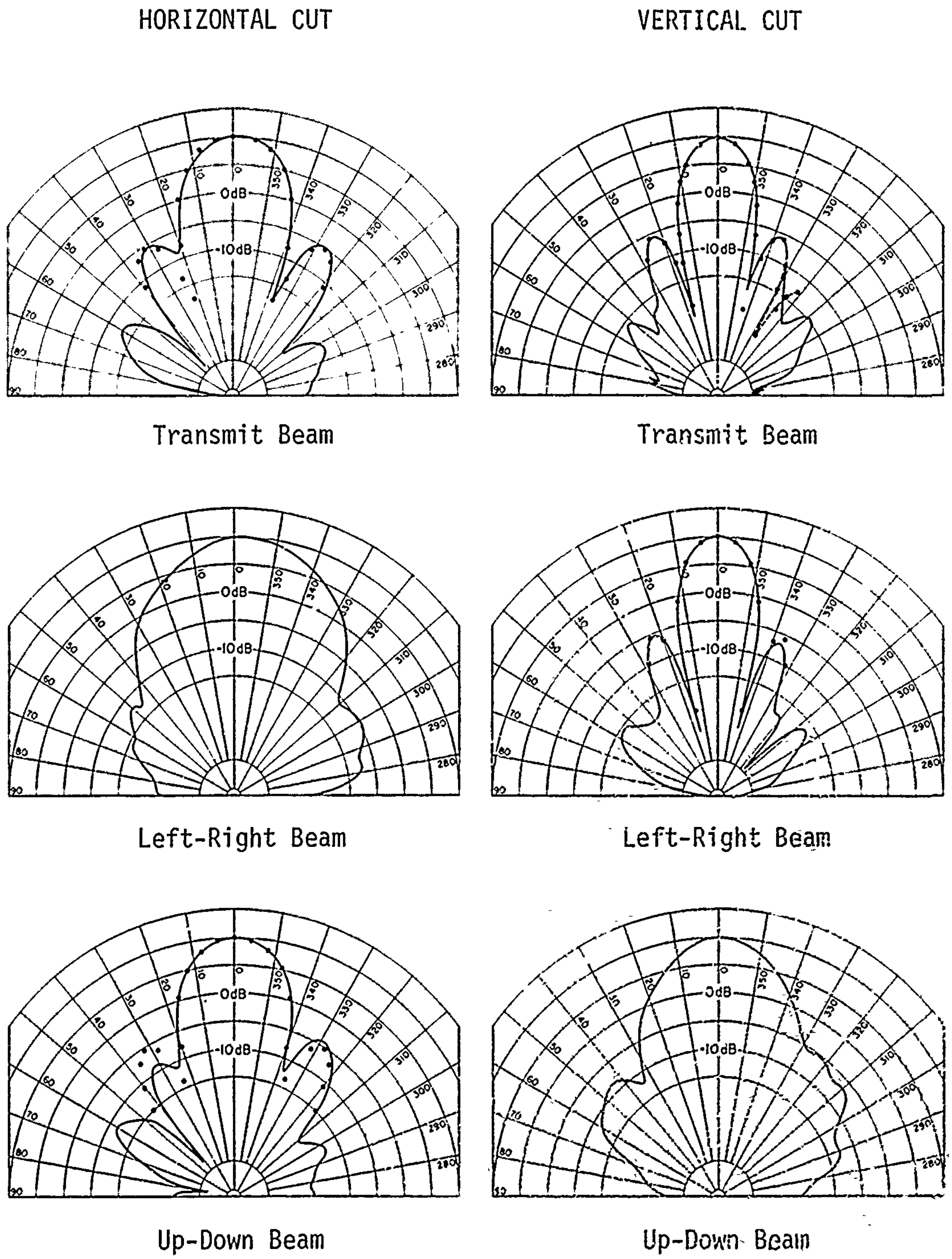
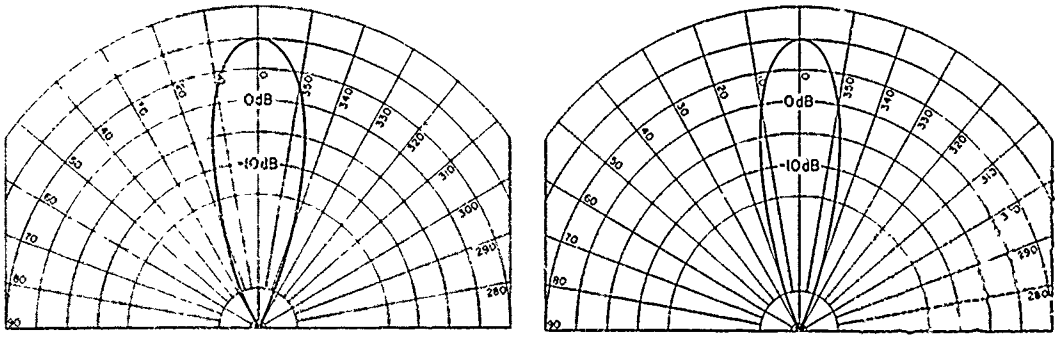


Figure 14. Calibration curves of an actual split-beam transducer. The isolated points are values of the equations fitted to the curves.

A different set of amplitude corrections is used in some of the simulations where the bearing, ψ, is zero, because of errors in calculating the beam patterns. In these simulations, which are denoted by an asterisk in Chapter 4, the vertical angle, THV, is set equal to zero for each fish. The amplitude corrections therefore are a function of only the horizontal angle, THH. A horizontal or vertical equivalent angle is computed using THH, and the combined transmit plus left-right and combined transmit and up-down amplitude corrections, BCL and BCU, are calculated. The section of the program code that computes these corrections is shown in Fig. 15. The corresponding beam patterns for BCL and BCU are shown in Fig. 16. The maximum difference in amplitude corrections for the two sets of beam patterns ranges from 0.09 dB for the small school to 2.17 dB for the large school. Since the effect

```
C CALCULATION OF BEAM CORRECTIONS
      THH=BR-ATAN2(Y(I),XR) $ THV=ATAN2(D,SQRT(XR**2+Y(I)**2))
      THVEQ=SQRT((THH/1.75)**2+THV**2)*10.60713
      THHEQ=SQRT(THH**2+(1.3*THV)**2)*7.1625454
      IF(THVEQ.LT..00001) GOTO 30
      E=2.*(.017189*THVEQ+.2)
      BCL(I)=((ABS(SIN(THVEQ)/THVEQ))**E-1.)*90.
      GOTO 35
   30 BCL(I)=0.
   35 IF(THHEQ.LT..00001) GOTO 40
      E=2.*(.017189*THHEQ+.2)
      BCU(I)=((ABS(SIN(THHEQ)/THHEQ))**E-1.)*90.
      GOTO 45
   40 BCU(I)=0.
   45 CONTINUE
```

Figure 15. Listing of the computer code used in calculating the second set of beam losses for schools denoted by an asterisk in Chapter 4.



Transmit and Left-Right Transmit and Up-Down

Figure 16. Combined transmit and receive beam patterns for the second set of amplitude corrections (denoted by an asterisk in Chapter 4).

of random amplitudes is found to be insignificant in Chapter 4, these differences in amplitude corrections, although they are based on the spatial properties of the fish, should not cause major changes in the spatial estimates. The dimension estimates may be slightly reduced because of greater beam losses for fish farther from the beam axis.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A SIMULATION STUDY ON THE SIZE AND ANGULAR LOCATION ESTIMATION OF FISH SCHOOLS USING SPATIAL CORRELATION		5. TYPE OF REPORT & PERIOD COVERED Technical 6. PERFORMING ORG. REPORT NUMBER APL-UW 8012
7. AUTHOR(s) Roger G. Hendershot		8. CONTRACT OR GRANT NUMBER(s) N00024-78-C-6018
9. PERFORMING ORGANIZATION NAME AND ADDRESS Applied Physics Laboratory University of Washington 1013 N.E. 40th, Seattle, WA 98105		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command Department of the Navy Washington, D.C. 20362		12. REPORT DATE August 1980 13. NUMBER OF PAGES 90
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Master's Thesis

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Acoustic simulations
Acoustic spatial correlation
High frequency acoustics
Hydroacoustic fisheries assessment
Reverberation generator (REVGEN)
Sonar false targets
Split-beam sonar
Underwater guidance and control
Volume reverberation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A computer simulation based on a point scatterer model has been used to investigate the problem of estimating the location and dimensions of fish schools using split-beam processing of hydroacoustic data. Estimates are derived from the temporal crosscorrelation of signals received by transducer halves, the peak correlation amplitude being related to the variance of the scatterer locations (the fish school's width) and the time shift of the peak being related to the → next page

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) mean of the scatterer locations (the fish school's angular position). These estimates are formed with vertically and horizontally separated transducer halves and combined with echo arrival time to provide three-dimensional position and size.

It is demonstrated that fluctuations in the estimated angular size decrease as the ratio of pulse length to echo length decreases.

The effect of additive noise, uncorrelated between acoustic channels, has also been studied. Noise causes width estimates to be biased toward larger values, owing to decorrelation between the acoustic channels. The location estimates, however, remain unbiased for signal-to-noise ratios down to approximately -5 dB.